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Low-temperature elastic properties of four wrought and annealed aluminium alloys

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The elastic properties of four annealed polycrystalline commercial aluminium alloys were studied between 4 and 300 K using a pulse-superposition method. Results are given for longitudinal sound velocity, transverse sound velocity, Young's modulus, shear modulus, bulk modulus (reciprocal compressibility), Poisson's ratio, and elastic Debye temperature. The elastic stiffnesses of the alloys increase 4 to 13% on cooling from room temperature to liquid helium temperature. The elastic constant–temperature curves exhibit regular behaviour.

1. Introduction

Aluminium alloys are used extensively at cryogenic temperatures because of their favourable mechanical properties. These properties include increased strength without loss of ductility at lower temperatures, absence of a ductile–brittle fracture transition, and, for some alloys, high strength-to-weight ratios.

Knowledge of a material's elastic constants is essential for understanding its mechanical behaviour. Most mechanical behaviour is best described by a dislocation model, and the elastic constants (usually the shear modulus and Poisson's ratio) occur in most equations describing the stress–strain state of a dislocated solid.

In this paper, the elastic properties of four wrought aluminium alloys (commonly designated 1100, 5083, 7005, and 7075) are reported over the temperature range 300 to 4 K. These properties include the longitudinal modulus, Young's modulus, the shear modulus, the bulk modulus (reciprocal compressibility), and Poisson's ratio. While the changes of the elastic constants in this temperature range are only moderate (4 to 13%), exact values of the elastic constants are very useful design parameters, permitting accurate calculations of deflections for any combination of stress and temperature. Low-temperature elastic constants are also quite valuable theoretically; they permit the calculation of the Debye characteristic temperature, which is related in turn to a wide variety of solid-state phenomena that depends on the vibrational properties of solids.

An ultrasonic (10 MHz) pulse-superposition method was used for determining the velocity, v, of a sound pulse propagated through the specimen. The elastic modulus, C, is then given by $C = \rho v^2$, where ρ is the mass density. Different elastic constants were determined from different modes of ultrasonic excitation. This method has many advantages: small specimens are sufficient, thus ancillary equipment such as probes and dewars can also be small, and refrigeration costs are low; specimens can have a simple geometry and can be easily prepared; measurements can be made as nearly continuously as desired; relative precision is high, about one part in 10^5 for the velocities; laboratory-to-laboratory variations of the elastic constants are typically a few percent or less; and tests are completely non-destructive.

Low-temperature elastic data for aluminium alloys have two-fold interest. First, the elastic constants provide basic information about interatomic forces. Second, the same numbers are essential design parameters for stress-bearing members. Data given here permit the load-deflection behaviour of the alloys to be accurately predicted between room temperature and liquid helium temperature. Accurate elastic data

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become especially important in applications involving high stresses, large structural parts, or precision parts.

2. Materials

Aluminium alloy 1100 is commercial quality aluminium. It has good corrosion resistance, high electrical and thermal conductivities, high ductility, but low strength properties. Strength can be improved somewhat by strain-hardening without significantly decreasing other properties. The main impurities in this alloy are usually iron and silicon.

Aluminium alloy 5083 is characterized by good welding properties and by good corrosion resistance in marine environment. Magnesium is the major alloying element and, along with manganese, produces a moderately strong, yet ductile alloy, which does not respond to heat-treatment. The strength properties of 5083 improve with lower temperatures. The main advantage of 5083 seems to be its weldability; welds as strong as the base metal can be obtained. Currently this alloy is being used in a number of applications involving the manufacture, transfer, and storage of liquefied natural gas; these applications require many millions of kilograms of material.

Aluminium alloy 7005 is a heat-treatable alloy containing zinc and magnesium, which are balanced to obtain a natural-ageing alloy. Chromium is added to reduce corrosion of the heat-affected weld zones, and zirconium is added to reduce weld cracking and to improve mechanical properties.

Aluminium alloy 7075 contains zinc as the major alloying element, together with a small percentage of magnesium. This alloy can be precipitation-hardened to produce high strength. (However, the studies reported here were made on annealed alloys.)

Details of compositions, heat-treatments, mass densities, and hardnesses of the alloys are given in Tables I and II.

3. Experimental

Alloys were obtained from commercial sources; 1100 and 7075 in the form of 1.9 cm rods, 5083 and 7005 in the form of 1.9 cm thick plate. Cylindrical specimens 1.6 cm diameter and 1.6 cm long were prepared by grinding. Opposite faces were flat and parallel within 2.5 μm. Specimens were annealed at a pressure of 5×10^{-6} Torr, or less, and cooled in the furnace. Hardnesses were determined by standard metallurgical methods, and mass densities were determined by Archimedes's method using distilled water as a standard.

Quartz transducers (10 MHz) were bonded to the specimens with phenyl salicylate for room-temperature measurements and with a stopcock grease for lower temperatures. In a few cases, failure of these bonds at very low temperatures required using a silicone fluid (viscosity = 2×10^3 P at 25° C) for bonding. The low-temperature apparatus was described previously [1].

A pulse-superposition method was used to determine the sound-wave velocities over the temperature range 300 to 4 K. Details concerning this method were given elsewhere [2].

4. Results

Quantities that were measured directly are the longitudinal and the transverse sound-wave

TABLE I Compositions of the alloys, mill analyses, wt %

Alloy	Al	Cr	Cu	Fe	Mg	Mn	Ni	Si	Ti	V	Zn	Zr
1100	Bal		0.2	0.6				0.1				
5083	Bal	0.13	0.04	0.19	4.75	0.63	0.003	0.08	0.01	0.007	0.04	
7005	Bal	0.25	< 0.1	< 0.4	1.2	< 0.2		< 0.3	< 0.1		4.6	0.3
7075	Bal	0.3	1.6	0.7	2.5	0.3		0.5	0.2		5.6	

TABLE II Properties of the alloys

Alloy	Hardness (DPH no., 1 kg load)	Mass density at 294 K (g cm^{-3})	Condition
1100	28	2.818	Annealed 345° C; furnace cooled
5083	78	2.666	Annealed 413° C, ½ h; furnace cooled
7005	77	2.779	Annealed 400° C, 3 h; furnace cooled
7075	67	2.721	Annealed 413° C, 3 h; furnace cooled

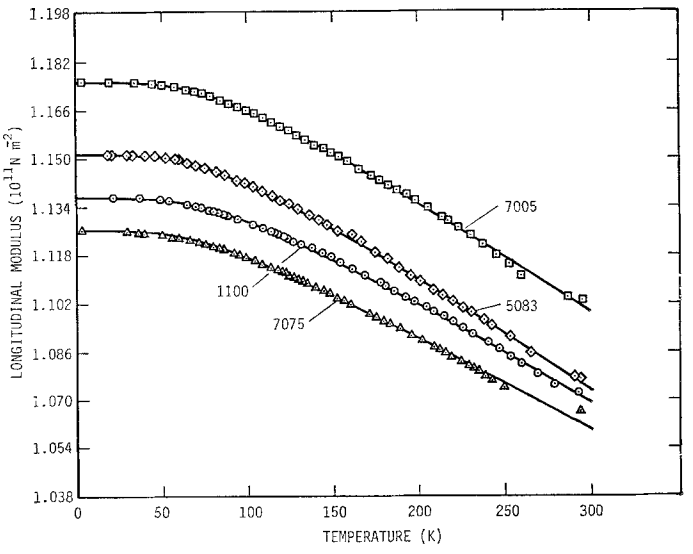

Figure 1 Temperature variation of the longitudinal modulus.

velocities v_l and v_t. From these, the longitudinal modulus, C_l, and the transverse modulus, C_t, were calculated according to

$$C_l = \rho v_l^2 \tag{1}$$

and

$$C_t = \rho v_t^2 . \tag{2}$$

These moduli are shown in Figs. 1 and 2 for the temperature range studied. No corrections were made for the change of mass density with temperature; for aluminium this introduces a maximum error, over 300 K, of 0.4%. Errors in the absolute velocities are believed to be about $\frac{1}{2}$% or less. All the other elastic constants that are used to describe polycrystalline aggregates are simply related to these two moduli. The moduli considered here – the shear modulus G, Young's modulus E, the bulk modulus B, and Poisson's ratio ν – are given by:

$$G = C_t , \tag{3}$$

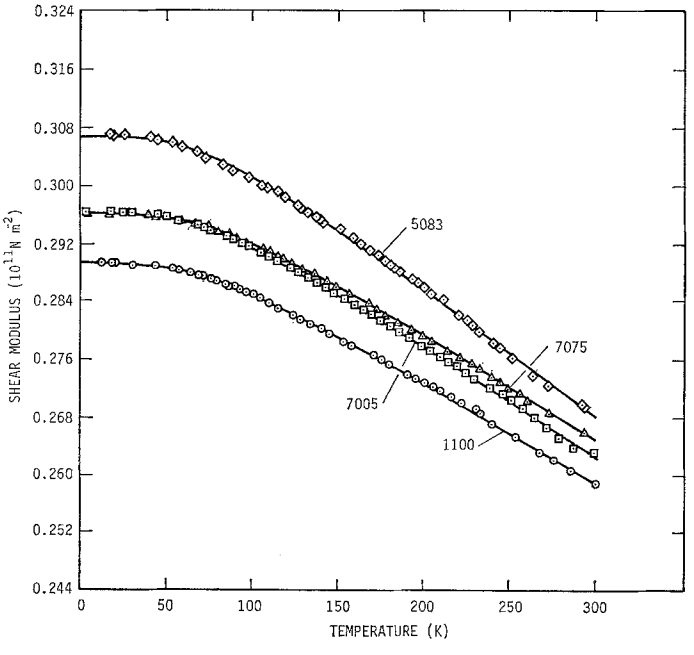

Figure 2 Temperature variation of the transverse or shear modulus.

$$E = 3G(C_l - \tfrac{4}{3}C_t)/(C_l - C_t)\,, \quad (4)$$

$$B = C_l - \tfrac{4}{3}C_t\,, \quad (5)$$

and

$$\nu = \tfrac{1}{2}(C_l - 2C_t)/(C_l - C_t)\,. \quad (6)$$

The elastic constants obtained from these relationships are shown as functions of temperature in Figs. 3 to 5. Values of the elastic constants at selected temperatures are given in Table III.

The temperature variations of the elastic constants can be described mathematically in various ways. In this case, the temperature dependences of both C_l and C_t were fitted to a theoretical relationship suggested by Varshni [3]:

$$C = C^\circ - \frac{s}{e^{t/T} - 1}\,, \quad (7)$$

where C is any elastic constant (C_l and C_t in this case), C°, s, and t are adjustable parameters and T is temperature. The value of C at $T = 0$ K is C°, and $-s/t$ is the high-temperature limit of the temperature derivative dC/dT. By invoking an Einstein oscillator model of solids, it can be shown (in the absence of electronic effects) that t is the Einstein characteristic temperature.

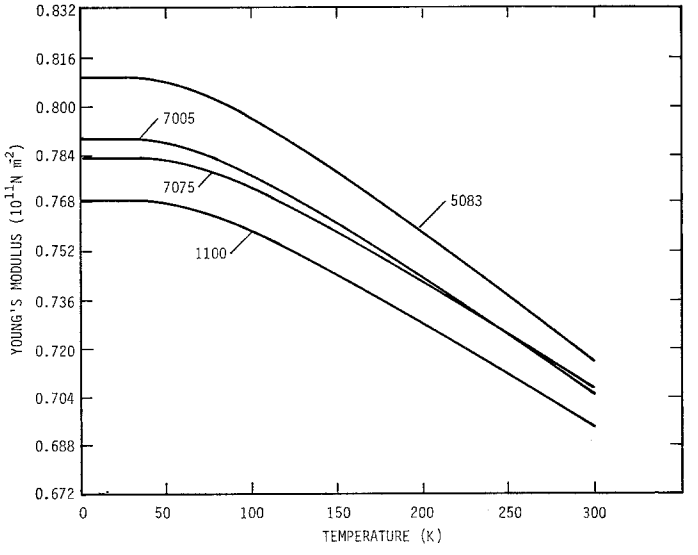

Figure 3 Temperature variation of Young's modulus.

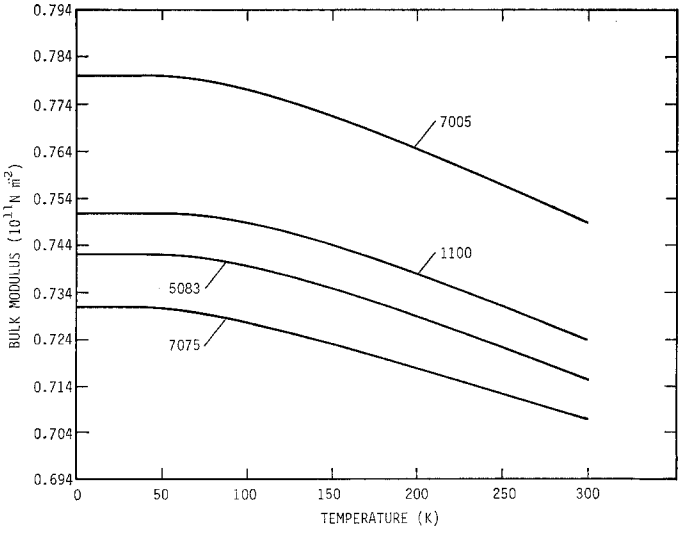

Figure 4 Temperature variation of the bulk modulus (reciprocal compressibility).

TABLE III Values of the elastic constants of aluminium alloys at selected temperatures in units of 10^{11} N m^{-2} except ν, which is dimensionless

	Present results					Previous results†					
Alloy	Temperature (K)	B	E	G	ν	Temperature (K)	B	E	G	ν	Reference
1100	300	0.724	0.694	0.259	0.340	300	(0.697)	0.689	0.258	0.33	[7]
	200	0.738	0.728	0.273	0.336						
	100	0.749	0.758	0.285	0.331						
	0	0.751	0.769	0.289	0.329						
5083	300	0.716	0.715	0.268	0.333	300	(0.762)	0.710	0.264	0.33	[7]
	200	0.729	0.758	0.286	0.327						
	100	0.739	0.796	0.301	0.321						
	0	0.742	0.809	0.307	0.318						
7005	300	0.749	0.705	0.262	0.343	300	(0.635)	0.711	0.271	(0.313)	[8]
	200	0.765	0.743	0.278	0.338	77	(0.735)	0.779	0.294	(0.323)	
	100	0.777	0.777	0.291	0.333	20	(0.671)	0.792	0.304	(0.303)	
	0	0.780	0.789	0.296	0.331						
7075	300	0.707	0.707	0.265	0.333	298		0.731			[9]
	200	0.718	0.742	0.279	0.328	200		0.786			
	100	0.728	0.773	0.292	0.323	20		0.786			
	0	0.731	0.783	0.296	0.321						
Alumin-	300	0.761	0.701	0.260	0.347						
ium*	200	0.777	0.738	0.275	0.342						
	100	0.790	0.771	0.288	0.337						
	0	0.794	0.784	0.293	0.336						

*Calculated from single-crystal data in [4].
†Entries in parentheses were derived using standard formulae.

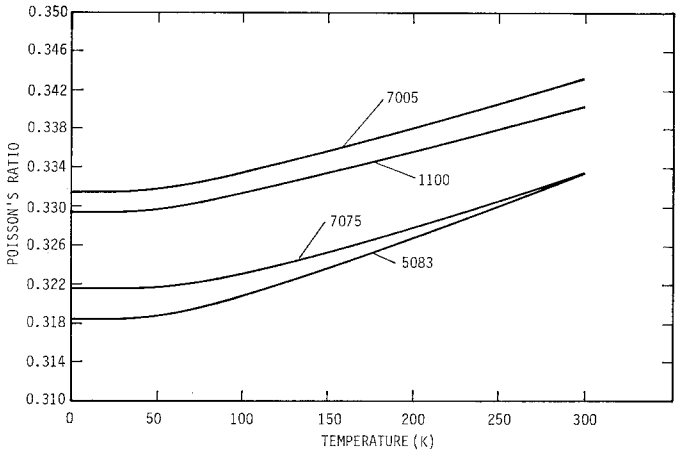

Figure 5 Temperature variation of Poisson's ratio.

Parameters C°, s, and t (determined by a least-squares fit of Equation 7 to the data) are given in Table IV. Average differences between

TABLE IV Parameters in Equation 7

Alloy	Mode	C^0 (10^{11} N m^{-2})	s (10^{11} N m^{-2})	t (K)
1100	l	1.136	0.0903	255.9
	t	0.2892	0.0301	206.9
5083	l	1.151	0.0926	235.3
	t	0.3067	0.0381	206.7
7005	l	1.175	0.0928	240.0
	t	0.2963	0.0327	203.4
7075	l	1.126	0.0707	219.6
	t	0.2961	0.0344	223.3

measured and curve values are 0.03% and 0.06% for the longitudinal and transverse moduli, respectively. Room-temperature values of the temperature coefficients of the elastic moduli are given in Table V; these values occur in the linear high-temperature region.

TABLE V Temperature coefficients of the elastic constants at room temperature (10^{-4} K^{-1})

Alloy	$\frac{1}{B}\frac{dB}{dT}$	$\frac{1}{E}\frac{dE}{dT}$	$\frac{1}{G}\frac{dG}{dT}$	$\frac{1}{\nu}\frac{d\nu}{dT}$
1100	−2.01	−5.01	−5.37	1.41
5083	−1.92	−6.06	−6.58	2.08
7005	−2.13	−5.48	−5.88	1.54
7075	−1.58	−5.08	−5.52	1.75
Aluminium*	−1.97	−5.53	−5.77	1.80

*Derived from single-crystal data in [4].

The elastic Debye temperature, θ, can be calculated from the elastic wave velocities by [5]:

$$\theta = K\langle v \rangle , \tag{8}$$

where

$$K = \frac{h}{k}\left(\frac{3N\rho}{4\pi A}\right)^{1/3} . \tag{9}$$

Here h is Planck's constant, k is Boltzmann's constant, N is Avogadro's constant, ρ is the mass density, and A is the effective atomic weight. The average velocity is given by

$$\langle v \rangle = \left(\frac{v_l^{-3} + 2v_t^{-3}}{3}\right)^{-1/3} . \tag{10}$$

The elastic Debye temperatures for the four alloys at $T = 0$ K, and also for unalloyed aluminium are given in Table VI.

TABLE VI Elastic Debye temperatures at $T = 0$ K

Alloy	θ (K)
1100	426.2
5083	440.4
7005	425.9
7075	422.2
Aluminium	430.6*

*Calculated from single-crystal data in [4].

5. Discussion

As shown by the data in Table III, changes in the elastic constants of aluminium and its alloys between 300 and 4 K are about 4% for B and ν, and 12% for E and G. These changes are somewhat larger than those observed in alloys based on copper or iron, for example. Most of the changes occur above about 100 K. Below this temperature the elastic constants change only slightly with temperature. Thus, any changes in the mechanical behaviour of these

alloys in this temperature region probably cannot be ascribed to an elastic origin.

The temperature behaviour of the elastic constants of the aluminium alloys reported on here is quite regular. The moduli decrease regularly with increasing temperature and the modulus–temperature curves are relatively flat at low temperatures. Also, in accord with the third law of thermodynamics, the slopes dC/dT approach zero at zero temperature. A linear temperature dependence is exhibited above about 150 K, which is roughly one-third of the Debye temperature. Besides indicating the absence of magnetic or structural transitions, this ideal temperature behaviour suggests that the anharmonic properties of these alloys can probably be explained by a relatively simple model.

These alloys were not examined for texture. However, texture would have little effect on their elastic properties. Aluminium single crystals are only slightly anisotropic; the Zener anisotropy ratio for aluminium is 1.2; it is 1.0 for the isotropic case. Aluminium's isotropy is purely accidental since aluminium, because of its three valence electrons, has a large band-structure contribution to the elastic constants [10]. This contribution is usually anisotropic; the anisotropy is cancelled in the case of aluminium by other energy terms. Thus, since aluminium single crystals are only slightly anisotropic, even a strongly textured polycrystalline aggregate of aluminium would have nearly isotropic elastic behaviour.

It should be emphasized that the data reported here are dynamic (adiabatic) rather than static (isothermal); they apply strictly to rapid rather than slow loading. However, the differences between adiabatic and isothermal elastic constants are small. They become smaller at lower temperatures because of the diminishing thermal-expansion coefficient, and they vanish at zero temperature. Using formulae given by Landau and Lifshitz [6] it can be shown for aluminium at room temperature:

$$\frac{E_S - E_T}{E_T} = 0.005\,, \quad \frac{B_S - B_T}{B_T} = 0.045 \quad (11)$$

$$\frac{\nu_S - \nu_T}{\nu_T} = 0.020\,, \text{ and } \frac{G_S - G_T}{G_S} = 0\,,$$

where subscripts S and T denote the adiabatic and the isothermal cases, respectively. For E, B, ν and G, these corrections are typically in the ratio 1:9:4:0 if ν has a value near $\frac{1}{3}$.

Effects of alloying on the elastic properties of aluminium cannot be accurately determined from the present study because of the large number of alloying elements and their interactions. Such effects have been considered elsewhere [11]. However, some general observations can be made concerning alloying. Disregarding alloy 1100, with respect to "pure" aluminium, the shear modulus and Young's modulus increased in all cases while the bulk modulus decreased, and by a larger percentage. Poisson's ratio decreased in all four alloys. The 1100 alloy, which contains only 1% of impurities, presents an interesting case. The data indicate that while the shear modulus of this alloy is identical to that of unalloyed aluminium, the bulk modulus is higher by about 5%. Since the bulk modulus is not measured directly, but is calculated from the difference of two velocities according to Equation 5, a compounding of errors may account for this discrepancy. If the effect is real, then it has important consequences for the problem of averaging single-crystal elastic coefficients to obtain the bulk modulus of a polycrystalline aggregate.

Finally, approximate relationships among the elastic constants are indicated. For all the alloys and for all temperatures, as a first approximation,

$$\nu \approx \tfrac{1}{3} \quad (12)$$

and

$$B \approx E \approx (8/3)G\,. \quad (13)$$

These should be useful for many engineering purposes where only rough numbers are needed and only one of the elastic constants is known.

6. Conclusions

From the results of this study the following conclusions are drawn:

(1) all the elastic properties of aluminium alloys 1100, 5083, 7005, and 7075 behave regularly with respect to temperature;

(2) for all alloys studied, the temperature behaviour of both C_l and C_t can be described accurately by a theoretical relationship suggested by Varshni;

(3) in this series of alloys, in the annealed condition, alloy 5083 has the highest Young's modulus, the highest shear (rigidity) modulus, and the lowest Poisson's ratio. Alloy 7005 has the highest bulk modulus.

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References

1. E. R. NAIMON, W. F. WESTON and H. M. LEDBETTER, *Cryogenics* **14** (1974) 246.
2. H. J. MCSKIMIN, *J. Accoust. Soc. Amer.* **33** (1961) 12.
3. Y. P. VARSHNI, *Phys. Rev.* **B2** (1970) 3952.
4. G. N. KAMM and G. A. ALERS, *J. Appl. Phys.* **35** (1964) 327.
5. P. DEBYE, *Ann. Phys. (Leipz.)* **39** (1912) 789.
6. L. D. LANDAU and E. M. LIFSHITZ, "Theory of Elasticity" (Pergamon, London, 1959) p. 17.
7. T. LYMAN, Ed., "Metals Handbook" (ASM, Metals Park, Ohio, 1961).
8. R. DEVELAY, A. FAURE, S. LEHONGRE, D. MUGNIER and D. SCHROETER, in "Advances in Cryogenic Engineering", Vol. 12, edited by K. Timmerhaus (Plenum, New York, 1967) p. 484.
9. J. L. CHRISTIAN and J. F. WATSON, *ibid*, Vol. 6, (1961) p. 604.
10. T. SUZUKI, *Phys. Rev.* **B3** (1971) 4007.
11. W. KÖSTER, *Z. Metallk.* **32** (1940) 282.

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