Ultralow Temperature Anelasticity of Aluminum-Magnesium Alloys

W. Duffy

► To cite this version:

W. Duffy. Ultralow Temperature Anelasticity of Aluminum-Magnesium Alloys. Journal de Physique IV Proceedings, 1996, 06 (C8), pp.C8-829-C8-832. 10.1051/jp4:19968178 . jpa-00254614

HAL Id: jpa-00254614

<https://hal.science/jpa-00254614>

Submitted on 1 Jan 1996

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Ultralow Temperature Anelasticity of Aluminum-Magnesium Alloys

W. Duffy Jr.

Department of Physics, Santa Clara University, Santa Clara, CA-95053, U.S.A.

Abstract. Results of internal friction measurements on the commercial aluminum-magnesium alloys 5052, 5086 and 5486 are reported here over the temperature range 50 mK to 300 K, and compared with published data on alloy 5056. Effects of heat treatment and explosive bonds on the internal friction are evaluated. The quality factor of proposed multi-layer aluminum-alloy spherical resonant-mass detectors of gravity waves is shown to be seriously degraded, if layer interfaces exhibit large-amplitude wavy explosive bonds. Shear modulus variations from 50 mK to 10 K are obtained from high-resolution frequency measurements.

1. INTRODUCTION

Although gravity waves were predicted by Einstein some 80 years ago, they have so far eluded terrestrial detection, in spite of intense activity by several experimental groups. Laboratories in Australia, Brazil, Europe, and the United States are currently active in the development of gravity wave telescopes based on *resonant mass detectors*.

These resonant mass detectors consist of multi-ton pieces of metal suspended by elaborate vibration isolators in vacuum enclosures, and cooled to very low temperatures to achieve high mechanical Q and low thermal noise. State-of-the-art transducers are attached to detect faint vibrational motion induced by the passage of a gravity wave. Detectors currently in operation can sense gravity-wave induced strains smaller than 10^{-18} . Improvements in strain sensitivity of two or more orders of magnitude are predicted for the most recently proposed omnidirectional spherical-geometry designs [1].

In 1980, Suzuki et al [2] first identified the aluminum-magnesium alloy 5056 as having a remarkably low internal friction (high Q) at temperatures as low as 4 K. Since that time, there have been a number of Q studies of various metals and alloys, yet 5056 seems to have retained its position as having the highest known low temperature Q of any aluminum alloy, and one of the highest that has been observed in any material available in large monolithic form. The most recently proposed resonant mass detectors would require aluminum alloy spheres with a diameter of 2.7 meters and a mass of 27 metric tons.

It has been proposed that the large sphere be produced by explosively bonding a stack of 25 to 100 aluminum alloy plates. A recent study by Duffy and Dalal [3] has demonstrated that high cryogenic Q s can be achieved in explosively-bonded Al-Mg alloys. The measurements reported here give the first Q -results at ultralow temperatures of several commercial Al-Mg alloys which may be viable alternatives to 5056, and in addition provide added information on the effect of explosive bonds on cryogenic Q s in these alloys.

2. EXPERIMENTAL PROCEDURE AND RESULTS

2.1 The experiment

Mechanical torsional resonators were machined from bar or plate stock of the commercial alloys 5052, 5086, and 5456. Two additional resonators were machined from 5086 alloy containing an explosive-bond plane. The resonator geometry may be seen in Fig. 1, as well as the location of the bond plane in those resonators which are made from bonded material. Typical overall dimensions are $D = 56$ mm and $L = 62$ mm.

The resonators were dimensioned to set the torsional mode of interest to about 1 kHz, the appropriate frequency for the resonant mass detectors. This mode is one in which the two inertial plates torsionally oscillate in phase opposition about the indicated symmetry axis. The thin central support disc is a node of the motion. The mode angular frequency is given by

$$\omega = d^2 \left[\frac{\pi G}{32 h I} \right]^{1/2}, \quad (1)$$

where G is the shear modulus and I is the moment of inertia of each inertial plate about the axis. The resonator is carefully machined to achieve "balance", i.e., so that no detectable torsional motion of the central support disc occurs when the mode is strongly excited.

Separate capacitive transducers located close to the sides of one of the inertial plates were used to excite the vibration and to detect the transient decay. Decay curves were checked for amplitude dependence, and the maximum strain amplitude was kept sufficiently small to avoid the effect. Typical amplitudes were in the range from 10^{-7} to 10^{-9} . Resonator temperature was measured with germanium resistance sensors. Additional experimental details have been published. [4]

2.2 Q measurement of monolithic material

Results of the Q measurements on three commercial Al-Mg alloys are given in Figs. 2 and 3. The data in Fig. 3 give the results for material which has been vacuum annealed for two hours at 500°C . On both figures the results of previously published measurements of the author [4] on a similarly configured resonator of 5056 are given for comparison. Quite similar results for the Q of 5056 were obtained by Coccia and Niinikoski [5] observing an extensional mode of a cylindrical bar at 35 kHz in the 0.1-10 K range of temperatures. In agreement with earlier work at 4 K and above, it is clear that alloy 5056 still is the material of choice among measured Al-Mg alloys for resonant-bar gravity-wave detectors. If the results on 5456 are excluded, there is apparent correlation between Q and magnesium content of the alloy. The results on 5456 are curious in that annealing reduced the cryogenic Q , which is unusual. In fact, Duffy and Dalal [3] in a similar explosively-bonded 5456 resonator did find the usual enhanced Q after a 475°C anneal, and somewhat higher Q -values than reported here. The microstructure in that case showed much more complete recrystallization than observed here. As is evident from Table 1, there is a wide range of concentrations of impurity elements in these materials, which along with the metallurgical variations may be expected to result in variations in Q from sample to sample of the same alloy.

Figure 1: Torsional resonator

Alloy	Mg wt %	Mn wt %	Cr wt %	Other imp max wt %	Grains	Hardness (Vickers)
5052	2.5±3	0.10	0.25±1	1.10	very elongated	46
5086	4.0±5	0.45±25	0.15±1	1.55	0.19 mm dia	51
5056	5.0±5	0.12±08	0.12±08	1.05	0.82 mm dia	53
5456	5.1±4	0.75±25	0.12±08	1.35	very elongated	66

Table 1. Material properties.

The origins of the very low acoustic dissipation observed in these alloys at temperatures below 10 K has received some attention in the dissertation of Marsden [6] and the book of Braginsky [7]. The magnesium, which is largely in solid solution, serves as an effective pinning site for dislocations. Reduction of internal friction which results from annealing is likely associated with a strong reduction of dislocation density produced by recrystallization. The high Q of 5056 has been associated with the high percentage of magnesium in this alloy. Since 5456 has about the same percentage of magnesium, it is surprising that it exhibits appreciably lower Q . The chemical composition of these two alloys is similar except for the sixfold higher level of manganese in 5456. Since the manganese is known to increase the recrystallization temperature, annealing the 5456 alloy at a higher temperature may have yielded higher Q .

Figure 2: Q vs T for as-machined alloys.

(Smooth curve is 5056 result.)

Acoustic relaxation near 3 K in Nb has recently been attributed to interactions with chains of dislocation kinks [8]. Dislocation motion which persists to temperatures of 1 K and lower may be associated with the motion of these kinks. Calculation of the second-order Peierls barriers to kink motion indicates that they are not larger than kT at 1 K in fcc crystals [9]. It is not clear, however, that this mechanism can explain the nearly flat internal friction curve vs temperature observed in these alloys at temperatures less than 10 K..

2.3 Q measurement of explosively-bonded material

Photographs of explosive bonds produced between 5086 alloy plates are shown in Fig. 4.. These explosive welds were produced by the DMC Corp., (Explosive Fabricators Div.), of Lafayette, Colorado, USA. These wavy bonds were intentionally produced in the material to ascertain whether this type of bond, which will probably be unintentionally present in the fabrication of the welded stack, introduces significant acoustic loss. Previously reported results on essentially flat explosive bonds in 5056 alloy and 5456 alloy [3] revealed only slight reductions in cryogenic Q as compared to monolithic material. Results of the Q measurements of explosively-bonded 5086 alloy are given in Fig. 5, along with the smooth curves corresponding to measurements on a similarly dimensioned resonator of monolithic material. As seen from Fig. 5, while the bond width of 0.5 mm exhibits a Q reduction of at most about 35% in the annealed material, the much thicker 5 mm bond produces a Q reduction of two orders of magnitude. (The bond widths given are equal to the double amplitude of the weld waves.)

Figure 3: Q vs T for annealed alloys.

(Smooth curve is 5056 result.)

a) 0.5 mm bond

b) 5.0 mm bond

Figure 4: The wavy bonds.

In order to evaluate the effect of these Q reductions on the quality factor of the proposed spherical gravity-wave antenna, it is desirable to attempt to extract the effective Q of the bond region from the measured resonator Q_s . If the quality factor of the alloy plate interiors is designated Q_A , and the quality factor of the bond region is Q_B , then one may show [3] that the Q of the resonator with an axial bond region as shown in Fig. 1 is given by

$$\frac{1}{Q} = \frac{(1-\lambda)}{Q_A} + \frac{\lambda}{Q_B}, \quad \text{where } \lambda = \frac{2}{\pi} \left[\frac{\delta}{3d} \left(1 + 2 \frac{\delta^2}{d^2} \right) \sqrt{1 - \delta^2/d^2} + \arcsin \delta/d \right] \quad (2)$$

and δ is the width of the bond. One may easily verify that for $\delta/d \ll 1$, $\lambda = 8\delta/(3\pi d)$.

Figure 5: Q vs T of bonded 5086.

Figure 6: Modulus increment vs T of monolithic alloys.

One can do a calculation analogous to equation (2) for the sphere, which relates the sphere Q to the Q_s of the bonds and the monolithic regions. The calculation is quite laborious because of the complexity of the quadrupole vibration modes of interest. For an approximation to this relationship one may make the simplifying assumption that the strain energy in the plate interiors and the bonds is proportional to their relative volumes. Considering a sphere of diameter $\mathcal{D}$ fabricated from a stack of N plates of equal thickness where $N \gg 1$, one obtains

$$\frac{1}{Q_s} = \frac{1}{Q_A} \left[1 - \frac{N\delta}{\mathcal{D}} \right] + \frac{1}{Q_B} \left[\frac{N\delta}{\mathcal{D}} \right]. \quad (3)$$

This equation is used to estimate values of Q_s for a 1000 Hz aluminum alloy sphere of diameter 2.7 m, fabricated from 1-, 2-, and 4-inch thick plates. These results are collected in Table 2. Previously reported results [3] on virtually flat bonds in 5056 are also listed.

Alloy	Bond width	Q_A	Q_B	Q_s N=27	Q_s N=53	Q_s N=106
5056	0.036 mm	39×10^6	14×10^5	38×10^6	38×10^6	37×10^6
5086	0.5	18×10^6	19×10^5	17×10^6	16×10^6	15×10^6
5086	5.0	18×10^6	75×10^3	14×10^5	74×10^4	38×10^4

Table 2. Calculated Q_s values of spherical gravity wave detectors.

2.4 Modulus measurements

From resonator frequency data, the incremental shear modulus results are given in Fig. 6 for annealed materials. The 5456 data is similar to previously reported 5456 and 5056 data. The peak at about 0.8 K is believed to correspond to the superconducting transition temperature. In 5052, the elemental impurity percentages are similar to those in 5056 and 5456 except for the magnesium, and they tend to decrease the critical temperature. Even the magnesium lowers the critical temperature at atomic concentrations less than about 4%. [10] Thus the apparent 0.1 K transition temperature is difficult to understand, as is the anomalous increase of G of about 2 ppm between 1 and 10 K.

Acknowledgments

The author would like to thank S. Dalal for help with the measurements. This work is supported by the U.S. National Science Foundation under grant PHY 9511613.

References

- [1] Merkowitz S.M. and Johnson W.W., *Phys. Rev.D* **51** (1995) 2546-2558.
- [2] Suzuki T., Tsubono K. and Hirakawa, H., *Phys. Lett.* **67A** (1978) 2-4.
- [3] Duffy W. Jr. and Dalal S., *Cryogenics* (1996) in press.
- [4] Duffy W. Jr., *J. Appl. Phys.* **68** (1990) 5601-5609.
- [5] Coccia E. and Niinikoski T.O., *Lett. al Nuovo Cimento* **41** (1984) 242-246.
- [6] Marsden, J.R., Ph.D. Dissertation, University of Rochester (1984).
- [7] Braginsky V.B., Mitrofanov V.P. and Panov V.I., *Systems with Small Dissipation* (University of Chicago Press, Chicago, 1985) pp. 10-41.
- [8] Pal'-Val' P.P., Natsik V.D., and Pal'-Val' L.N., *Low Temp. Phys.* **21** (1995) 505-517.
- [9] Fantozzi G., Esnouf C., Benoit W. and Ritchie I.G., *Prog. Mat. Sci.* **27** (1982) 311-447.
- [10] Rapp O. and Fogelholm R., *J. Phys. F* **5** (1975) 1694-1705.