MATERION

DATA SHEET

Acoustic Properties of Beryllium

Abstract

Beryllium is widely used for a variety of special applications which utilize one or more of beryllium's unique combination of properties including:

1. High stiffness to density ratio
2. Good strength to density ratio
3. High heat capacity and thermal conductivity
4. High atomic scatter cross section and low absorption cross section

Keywords: Dimensional stability, ultrasonic applications, high stiffness of density, high heat capacity, thermal conductivity, Debye temperature, fatigue endurance limit

Dimensional Stability

In addition, other properties which make beryllium unique among metals for its acoustic characteristics and make it potentially attractive for certain structural and coupling components in ultra¬sonic systems are:

1. A velocity of sound which is approximately two times that of other metals
2. An unusually low Poisson's ratio
3. A very high Debye temperature

Velocity of Sound

The velocity of longitudinal sound waves in beryllium is about 13,000 meters/second. This is compared to sound velocities of other materials in Table I. Compared with aluminum, magnesium and titanium alloys which are already finding their way into ultra¬sonic applications, the velocity in beryllium is almost twice that of the other metals.

This higher velocity means an increased wavelength for any sound wave in the structure or a higher resonant frequency for the structure, thus reducing the chance for destructive resonance under random excitation. For this reason beryllium is sometimes referred to as a "high damping" material. (This differs from the important considerations of amplitude damping by internal friction discussed subsequently.)

On the other hand, intentional resonance, as in vibrating reed filters, switches, etc., can be more precisely controlled with beryllium since the resonating component could be made much longer than if made of other metals.

Poisson's Ratio

The Poisson's ratio of beryllium is unusually low. (This is the ratio of the elastic change in area to the change in length under uniaxial loading.) Reported values range from 0.01 to 0.085; the 0.01 value being obtained by an ultrasonic technique. The most commonly accepted value is 0.02, as compared with values of 0.3 to 0.4 for other metals.

In ultrasonics, a low Poisson's ratio means reduced coupling of sound waves from one mode of propagation to another. For example, a shear wave will remain a shear wave without trans¬ferring energy to a longitudinal mode of wave propagation. This ability to keep the different modes of propagation separated can be of great importance in acoustic imaging and surface wave devices, where the signal could be totally confused if it is trans¬ferred into several interacting propagation modes, each with its own velocity of propagation and with its own dispersion relationships. A low Poisson's ratio also means that nodal mountings of transducer structures are more effective in reducing energy losses, detuning, etc., by the mounting. This is because the transverse motion at the node is reduced (by the low Poisson's ratio) along with the longitudinal motion.

In this connection, beryllium also has an unusual combination of single crystal elastic constants and lattice spacings. Most remarkable is the C13 ratio of -0.01 which means that acoustic waves along the c-axis are completely uncoupled from acoustic waves in the basal plane. No other metal exhibits this phenomenon.

Debye Temperature

The attenuation of sound waves is very important in ultrasonics. It affects the sensitivity of low amplitude (low power) sensing and imaging devices, and it reduces the efficiency of higher power devices.

The attenuation, sometimes called amplitude damping, arises as a result of internal friction within the material. In solids there are several mechanisms for this internal loss of oscillatory energy. Some of these mechanisms involve thermal diffusion, dislocation motion, magnetic effects and impurity concentrations, grain size and isotropy of the crystallographic properties. In general the losses are dependent on frequency, temperature and stress ampli¬tude, and, in general, the rate of dissipation increases with increasing mean stress and stress amplitude, and may be affected by the stress history and heat treatment.
The thermal effects are particularly important at the higher ultra¬sonic frequencies and, in metals, relate closely to the Debye temperature.

The stress amplitude effects are very important in high power ultrasonic devices and relate closely to the fatigue characteristics of solids. The acoustic losses in metals which are attributable to thermal effects and which increase with temperature and frequency are of major concern in ultrasonic systems. However, they are not very important in a material at temperature below about half the Debye temperature.

Very simply, the Debye temperature is the maximum temperature at which the crystal lattice is "ordered"; it is generally high for materials of low compressibility, and of high melting point coupled with low atomic weight. The Debye temperature of beryllium, at 1000°K, is more than two times that of other metals. Since most metals at room temperature are above half of their Debye temperatures, the acoustic losses in beryllium, especially at high frequencies, will be considerably less than in other metals. This appears in the values at one GHZ (near the upper end of the practical ultrasonic range) as indicated in Table I, under "attenu¬ation at 1 GHZ" .

At very high frequencies, the attenuation of beryllium is a factor of 100 less than in aluminum and magnesium. (Quartz shows even less attenuation but it is not usable for significant power levels at these high frequencies and is not fabricable into the shapes commonly needed for acoustic systems.) At the lower end of the ultrasonic spectrum (below about 30 KHZ) beryllium does not have a great advantage (again, shown in Table I), but at higher frequencies the attenuation in beryllium will be significantly less than in other metals.

Fatigue Endurance Limit

The fatigue endurance limit is the stress above which a material will fail in ultrasonic application, since total cycles of operation will be many orders of magnitude greater than the 108 limit to which metals are usually tested.
In high power ultrasonic devices, the stress amplitudes can easily reach levels which will result in fatigue failure of horns, and other elements.

At lower stress amplitudes, the internal friction will depend on the stress amplitude as a proportion of the endurance limit, increasing very steeply above eighty percent (80%) of the fatigue limit.

The endurance limit of beryllium can be as high as 35 ksi for hot pressed block and up to 65 ksi for extrusions. On a weight basis (the endurance limit/density) beryllium is about twice as good as light weight structural alloys of aluminum and titanium and about ten times as good as steel.

Impedance

The acoustic impedance is an important characteristic of materials for nearly all sonic and ultrasonic applications. As in the electri¬cal analogy it will determine the efficiency of every transmission in the system from one element to another. A mismatched impedance between a transducer and a work piece (or working fluid) can be improved by the insertion of an intermediate quarter-wave "stub" or buffer plate. The impedance of the buffer plate should be near the geometric mean of the two adjoining impedances. Even better efficiencies sometimes may be obtained by inserting two buffer plates, again with each impedance being as nearly as possible to the geometric mean of its adjoining impedances.

As is shown in Table I, the impedance of beryllium falls, with titanium, between magnetostrictive materials and magnesium or structural plastics, and the relative impedances are such as to make beryllium useful as a buffer or acoustic lens element.

ACOUSTIC PROPERTIES OF VARIOUS MATERIALS (A)

Material	Density (gm/cm^3)	Young's Modulus (N/m^2 x 10^{-10})	Poisson's Ratio(a)	Longitudinal Velocity (m/s x 10^{-3})	Wave Impedance (kg/m^2 s x 10^{-6})	Debye Temp (°K)	Attenuation at <30 KHz (Q^{-1} x 10^4)	At 1 GHz (nepers/m x 10^{16})	Fatigue Endruance Limit (N/m^{2}x10^{-7})
Aluminum	2.70	7	0.36	6.4	17	398	1-5	2.1	2-6
Al Alloy	2.79	7-11	0.34	6.3	17	--	2-7	~2.3	6-23
Beryllium	1.85	31	0.02	12.9	24	1000	1-3	0.02	24-25
Copper	8.9	12	0.37	5.0	45	315	20-64	4.4	<9
Iron	7.8	21	0.29	6.0	46	88	3-18	--	~10
Lead	11.4	1.5	0.43	2.0	22	290	20-30	30	0.5
Magnesium	1.74	4.2	0.31	5.8	10	370	~5	2	<15
Nickel	8.9	21	0.34	6.0	53.	--	!3	0.4	23-34
Stainless Steel	7.91	20	0.30	5.8	46	--	2	--	27
Titanium	4.50	10.5	0.34	5.9	27	--	~8	--	<28
Ti Alloy	4.5	11.5	--	6.1	27	310	~10	--	75-100
Tungsten	19.2	36	0.35	5.4	103	--	2-8	0.5	--
Fused Quartz	2.5	7.3	0.17	6.0	13	--	--	(b)	--
Polyethylene	0.93	--	--	1.9	1.8	--	--	--	--
Water	1.0	--	--	1.6	1.4	--	--	0.0062	--
Air	1.2 x 10-3	--	--	0.33	0.0004	--	--	--	--
Barium Titanate	5.6	11.8	--	-5.5	24	--	25	--	--
Quartz O° X-Cut	2.65	8.0	--	~6	15	--	0.01	--	--

(a) The values shown are a reconciliation of data from various sources, material and test conditions.
(b) Although reported values are very small (2.6 x 10-22), fused quartz is not usable at these frequencies.

There are two related specialties in the general field of ultrasonics which are developing very rapidly, even in comparison with the rapid growth of the ultrasonics industry as a whole; and both of these rely heavily on the use of acoustic lenses. These are the areas of undersea imaging (mostly sonar for military applications), and acoustic holography (mostly non-military, industrial and medical applications). These lenses have been as large as two feet in diameter by several inches thick and will be larger in future systems. The materials presently used (polystyrene, aluminum, magnesium and titanium alloys) are relatively inefficient, with respect to the transmission of acoustic energy. Beryllium is tech¬nologically feasible and appears to be economically justifiable for these applications, either, for the lens itself or as a buffer between the transducer and lens, or as one element of a two-¬element lens.

Because beryllium is a powder metallurgy product, it might, for impedance matching or grading purposes, be tailored to a particular impedance by mixing it, in the form of a composite, with higher impedance powders. But at most frequencies this could cause a prohibitive increase in scattering and acoustic losses in the material. In the extreme, this technique could be used to inten¬tionally increase acoustic attenuation, for a low inertial struc¬tural material with noise and vibration damping characteristics. Such a material might be economical for phonograph tone arms, special tweeter diaphragms, etc., to eliminate resonances.

MISCELLANEOUS

The specific heat of beryllium at room temperature is 0.46 gm calories/°C. In fact, beryllium has a higher heat capacity than any other metal. For any given weight and temperature increase it will absorb two times as much heat as either aluminum or magnesium and three times as much heat as titanium.

The thermal conductivity of beryllium at room temperature is 104 Btu-ft/ft2-hr-°F which is comparable to that of aluminum. The coefficient of thermal expansion at room temperature is about 11.5 x 10-6/°C. This closely matches with coefficients of thermal expansion for stainless steel, nickel alloys and cobalt alloys.

The thermal diffusivity of beryllium assumes rapid temperature equalization which tends to eliminate or greatly reduce distortion that might otherwise be caused by thermal gradients.

In addition to the above properties, the following characteristics further enhance the versatility of beryllium:

1. A protective surface similar to that on aluminum is formed in air, and oxidation at elevated temperature is not excessive below 815°C.
2. Its electrical conductivity is 40°% IACS.
3. It is non-magnetic.
4. It reflects light; while light reflectivity 50%, ultraviolet light reflectivity 55%, infrared reflectivity 98%.

APPLICATIONS

The most obvious potential acoustic application of beryllium is in rotating shafts, structural members, and device components in which resonance at rotational frequencies or due to random excitation would be damaging or detrimental to the device per¬formance. In other components in which resonance is desired (such as vibra¬ting reed type devices) a larger and consequently more precise component might be practical with beryllium.

As mentioned earlier, a potential application is for buffer plates (or 1/4 wave stubs) to acoustically match impedances of transducer components. In this application the beryllium buffer would tend to suppress reflection losses and thereby improve efficiency of ultrasonic welders, sealers, etc. When used as a buffer plate, beryllium would offer the added advantages of light weight, heat capacity and thermal stability to help dissipate waste heat from the transducer and in some cases could avoid the need for auxiliary cooling.

Similarly, due to its inherent impedance matching to plastics it could be used for lenses and lens elements within transducer housings which would yield high-resolution ultrasonic detection systems with better efficiency than that presently available using small-diameter detectors. The relatively low attenuation of ultra¬sonic waves (low loss of acoustic energy) in beryllium, in the high frequency range now being used in these systems, will result in increased detection sensitivity and improved signal to noise ratios. If, as we presently believe, this attenuation in beryllium proves along with the ultrasonic velocities to be less dependent on frequency than in the other materials, it will have even greater advantage in maintaining ultrasonic pulse shapes and resolution of images.

The low Poisson's ratio of beryllium also is a great advantage. This too is with respect to the resolution of acoustic energy, by reducing intermodal coupling within the lens. It helps maintain pulse shape as well as pulse energy. The high index of acoustic refraction results from the relatively high velocity of sound in beryllium. It means among other things that the change of direction of an acoustic wave at an interface (as between beryllium and polystyrene) will be relatively high, which could be an advantage in many systems. The relatively high velocity of sound can also result in improved impedance matching and consequently improved efficiency and sensitivity in some instances.

Certain types of speakers and ultrasensitive microphones as well as stable light weight hydraphone reflectors might benefit from beryllium components (or composites containing beryllium). In some instances, such as in high power speakers, the high heat capacity and power dissipating ability of beryllium could be an advantage. Here and in other devices, its electromagnetic damp¬ing (Foucault damping) characteristics could also be important. Beryllium has about the same electromagnetic damping characteris¬tics as aluminum, but has a higher modulus and can operate at higher temperatures.

Shakers for fatigue testing and accelerometers for various systems might benefit from the strength-to-density ratio of beryllium, since weight reduction is generally important in these devices. Beryllium is already in use as a core material in accelerometers for its high resonant frequency and low density and in some instances for its coefficient of thermal expansion, which can be varied over a range of about fifteen percent by texturing. Certain ultrasonic delay lines might benefit from substitution of beryllium as the delay media and beryllium might be used in either single crystal or polycrystal form) in surface wave devices for low attenuation, as well as high wave velocity.

CONCLUSION

The field of ultrasonics is developing rapidly and specialists in this area are constantly looking for materials which will improve the sensitivities and efficiencies of their systems. Beryllium offers a unique combination of acoustic properties that is not found in any other structural material; and it is particularly attractive for the higher frequencies (> 10 MHz) now coming into common use.

This booklet is not intended to be a complete listing of all of beryllium's acoustic properties, rather it is designed to stimu¬late the thinking of engineers engaged in the design of acoustic devices. Brush Wellman materials technologists are skilled in working with customers in developing design data needed and in modifying beryllium to better meet specific requirements. This service is available in response to any inquiry.

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Note:
Handling Aluminum-Beryllium Alloys in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals.

The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material.

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