INTERLABORATORY STUDY OF DAMPING CAPACITY IN LEADED BRASS AND LEAD-FREE BRASS

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ABSTRACT

By pooling the resources of three laboratories, the damping in leaded brass and lead-free brass has been explored over a wide range of variables, including frequency (0.03 Hz to 80 kHz), strain amplitude (10^{-7} to 7×10^{-4}), temperature (25 to 400°C), and vibrational modes (longitudinal and flexure). For investigations at frequencies less than 50 Hz, cantilevered beams were tested, at frequencies in the range 0.03 to 200 Hz, fixed guided beams (Dynamic Mechanical Thermal Analyzer, DMTA) were used, while the high frequency (80 kHz) studies were performed with the PUCOT (Piezoelectric Ultrasonic Composite Oscillator Technique). The results from the DMTA experiments yielded an effective activation energy of about 1.67 eV/atom for the initiation of rapid increases in damping as a function of temperature. This value is close to the value of 1.7 eV/atom found by Youssef for the short-range ordering process of Zn and Cu atoms these type of alloys. The PUCOT results for the leaded brass revealed a strong damping peak near 327°C, the melting point of the lead inclusions. This peak is denoted as transient liquid phase (TLP) damping. The amplitude dependence data on leaded brass showed that the break away effect, where the amplitude independent damping changed to amplitude dependent damping, was temperature dependent, with a maximum break away stress of over 2 MPa near 270°C. This temperature was close to the 280°C value observed by Youssef for short-range ordering of Cu-Zn alloys. The PUCOT data agreed well with the earlier results of Wolfenden and Robinson on similar alloys. On the other hand, no damping peaks near 327°C were found for the lead-free brass. The results of this study confirmed that TLP damping is a mechanism that offers possibilities of enhancing the level of damping in alloys containing low melting point inclusions. Taking into consideration the thermoelastic (Zener) effects for flexural damping, the damping data from the three laboratories were compared to see if consistent and reliable results could be obtained.

INTRODUCTION

The search for materials with high stiffness and high intrinsic damping continues, driven by the needs of the aerospace and space industries, and by developments within the US Department of Defense. In this study, the intrinsic damping of materials is approached from a fundamental point of view. There is no standard technique for the measurement of damping and, as a result, several instruments that measure damping for different vibration modes over different ranges of temperature, strain amplitude, and frequency have been developed. To assess the accuracy, repeatability, and reliability of the experimental methods, specimens from the same stock have been tested and the corresponding data compared. This research focussed on the following areas: thermoelastic (Zener) damping, transient liquid phase (TLP) damping, dislocation break away phenomena, and short-range ordering effects. The basic aim of the present research was to measure and analyze the damping in brass as a function of temperature, frequency, strain amplitude, lead content, and vibration mode.

MATERIALS

For this study, two types if brass alloys were used: 1) lead-free brass and 2) leaded (free-machining) brass. The lead-free bar stock came in two compositions and thicknesses. Thick samples (3.18 mm original thickness) had a composition by weight of 59.1% Cu, 38.1% Zn, and less than 0.05% Pb. The thin bar stock (1.59 mm original thickness) had a composition of 68.8% Cu, 29.0% Zn, and less than 0.05% Pb. The composition by weight of the leaded brass was 61.4% Cu, 35.4% Zn, with 2.65% Pb. Specimen sizes were tailored for the three instruments used for the damping measurements.

INSTRUMENTATION

The three instruments used for the damping measurements were the Cantilevered Beam (CB), the Dynamic Mechanical Thermal Analyzer (DMTA), and the Piezoelectric Ultrasonic Composite Oscillator Technique (PUCOT). Details of these techniques have been reported elsewhere [1-5]. The typical sizes of the specimens used in the three instruments were 250 x 12 x 2.1 mm, 34 x 6 x 1 mm, and 50 x 2 x 1.6 mm, respectively. The CB technique performed damping measurements in the frequency range of 15 to 50 Hz, in a vacuum environment, and at room temperature. The DMTA was used for measurements at frequencies in the range of 0.03 to 200 Hz, at temperatures in the 25°C to 340°C range, and in an air environment. The PUCOT operated at 80 kHz, covering the temperature range of 25°C to 400°C, with the specimens in an air environment. The strain amplitudes for the three techniques were 5×10^{-5}, 5×10^{-4} to 8×10^{-4}, and 10^{-7} to 10^{-4}, respectively. The CB and DMTA instruments used the flexural vibration mode, while the PUCOT used the longitudinal vibration mode.

RESULTS AND DISCUSSION

1. *CB Technique*

Figures 1-6 show the damping as a function of applied frequency for leaded and lead-free brass. There are numerous definitions for damping in current use. For the CB technique, the applicable definition is:

$$\Psi = \Delta W / W, \qquad (1)$$

where ΔW is the energy dissipated during one cycle and W is the maximum stored energy. Furthermore, the three definitions used in this interlaboratory work are related by:

$$\Psi = \Delta W/W = 2\pi \tan \delta = 2\pi Q^{-1}, \tag{2}$$

with tan δ (δ is the loss angle) measured by the DMTA and Q^{-1}, the internal friction, measured by the PUCOT. The continuous curves in Figs. 1-6 is the thermoelastic damping due to the Zener effect [6,7] that is given by:

$$\Psi/\Psi_0 = (\omega\tau) / (1 + \omega^2\tau^2), \tag{3}$$

$$\Psi_0 = (2\pi\alpha^2 ET) / (\rho C_p), \tag{4}$$

$$\tau = (h^2\rho C_p) / (\pi^2 k), \tag{5}$$

where Ψ_0 is a characteristic damping, τ is a characteristic time of the problem, ω is the circular frequency, α is the coefficient of thermal expansion, T is the absolute temperature, ρ is the mass density, C_p is the thermal capacity (at constant pressure) per unit mass, and k is the thermal conductivity. These physical properties for the two types of brass used in this study are listed in Table I. The total damping measured by the CB technique is thermoelastic damping plus the intrinsic damping due to all other sources. Therefore, it is reassuring to note that the thermoelastic damping serves as a lower bound for all measurements. The difference between the measured values and the Zener curve is attributed to dislocation damping. In Figs. 5 and 6, the damping data are plotted in accordance with the universal damping curve for brass (Eq. 3).

Table I - Physical properties of two types of brass at room temperature (21°C).

	Lead-free	Leaded
Coefficient of thermal expansion (K^{-1})	18.9×10^{-6}	18.9×10^{-6}
Young's Modulus (GPa)	103	103
Mass Density (g/cm^3)	8.44	8.49
Specific heat ($J\ kg^{-1}\ K^{-1}$)	385	385
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	144.1	144.1

2. *DMTA Technique*

Figures 7 and 8 show representative plots of damping (tanδ) as a function of temperature for lead-free and leaded brass, respectively, at several frequencies. Figure 7 indicates that the damping is low and essentially constant up to temperatures near 200°C, where the damping levels begin to rise. The temperature at which the damping begins to rise, called the activation temperature, increases as the frequency increases. Similar trends are observed in Fig. 8 for leaded brass. The curve for the test at 200 Hz seems to give anomalous behavior which is believed to be due to improper equipment functioning at this frequency. Using temperature estimates from Figs. 7 and 8, plus data from other DMTA tests on the same material, the frequency dependence of the activation temperature (T_a) for these alloys was examined. It should be noted that there was no significant difference in activation temperatures between the leaded and lead-free brass. Figure 9 shows the plot of the natural logarithm of the frequency versus the reciprocal of the activation temperature. The data are approximately linear, suggesting that the frequency and temperature can be related by an equation of the form:

$$f = f_0 \exp(-H/RT_a), \text{ or} \tag{6}$$

$$\ln(f) = \ln(f_0) - (H/R)(1/T_a), \tag{7}$$

where H is an effective activation energy for the increase in damping with temperature, R is the gas constant, and f_0 is a constant parameter. The slope of the plot yields an effective activation energy of 1.67 eV/atom or 38.3 kcal/mole. This value is close to the value of 1.7 eV/atom found by Youssef [8] for the short-range ordering process in Cu-Zn alloys, being equal to the activation energy for Zn diffusion in coarse-grained Cu. These results suggest that a diffusion damping mechanism causes the rise in damping in the frequency range covered by the DMTA.

Figure 10 shows the damping as a function of frequency for the leaded brass at 30°C. The data indicate the trend typical of thermoelastic damping with a peak between 3 and 10 Hz. This result is similar to those from the CB experiments, but the strain amplitudes used were an order of magnitude higher with the DMTA. Thus, one would expect there to be increased dislocation damping in specimens tested in the DMTA. This is the case for the data from this study (note that values for CB need to be divided be 2π for direct comparison), as, for example, the peak value from the DMTA is 2.5 times larger than the peak value from CB measurements. This difference is greater than expected and indicates possible problems with the accuracy of the damping measurements by the DMTA under the current testing procedures.

3. *PUCOT*

An Arrhenius plot of the damping data for leaded brass and lead-free brass is shown in Fig. 11. Clearly, there are significant differences in the damping curves for the two types of brass. The lead-free brass shows smoothly increasing damping as temperature increases, with no sign of damping peaks. On the other hand, the curves for the leaded brass show small peaks in damping near 280°C and near 327°C. These results have been discussed earlier [4] in terms of the melting of lead inclusions at and near the grain boundaries in the leaded brass. The strain amplitude dependence of damping for leaded brass at several temperatures is given in Fig. 12. The curves show the classical strain amplitude independent damping at low strains, and the amplitude dependent damping at higher strains. This behavior, in terms of the Granato Lücke (GL) dislocation damping theory [9], represents the break away of dislocations from their minor pinning points, resulting in increases in damping. The break away stress needed to free dislocations from their anchor points can be calculated from plots such as those in Fig. 12 by determining the break away strain and converting it to a stress via the Young's modulus of the materials. Figure 13 shows a plot of the break away stress as a function of temperature for leaded brass with some earlier data by Wolfenden and Robinson [4] on a similar material included. There is a pronounced peak in stress at 270°C, which is near to the temperature of 280°C observed by Youssef [8] as the short range order-disorder temperature in Cu-Zn alloys of similar composition to those used in this work. Thus, it appears that the details of the disordering process affect the ease with which dislocations can break away from their pinning points under the application of a vibratory stress.

4. *Comparison of Data*

Figure 14 shows the damping data obtained from room temperature tests on the lead-free brass and leaded brass. It is emphasized that the damping data from the CB have been corrected to extract out the portion (≈2/3) of the damping arising from thermoelastic (Zener) effects. For the lead-free brass, the data from the CB and PUCOT techniques agree with each other to within a factor of 1.3, while the results for leaded brass agree within a factor of two. These levels of agreement are good, especially when considering the low damping levels present. The DMTA results, not shown in Fig. 14, were considerably higher than those from the CB and PUCOT. It is felt that DMTA technique has not been sufficiently optimized to provide accurate measurements of the damping levels when the damping is low, as is the case for these alloys at room temperature. However, the activation temperature results from the DMTA testing, where the ability to detect changes in damping as a function of temperature, are promising and further optimization of the technique is in progress.

SUMMARY

From this interlaboratory study of the damping in lead-free and leaded brass the following summary statements and conclusions can be listed:

1. The measurements of damping over the wide range of experimental variables used in this study require the use of more than one instrument.

2. A comparison of the damping data from the three instruments (CB, PUCOT, and DMTA) for the two types of brass measured at room temperature revealed that the CB and PUCOT techniques gave essentially identical measurements of damping (when allowances were made for thermoelastic damping), whereas the DMTA measured higher damping, possibly due to a systematic error.

3. The results from the DMTA instrument yielded an effective activation energy of 1.67 eV/atom for the rapid increase in damping as a function of temperature for temperatures below 300°C. This activation was close to that found by Youssef for the short-range disordering process of Zn and Cu atoms in similar alloys.

4. The PUCOT results for the leaded brass revealed a strong damping peak (TLP camping) near 327°C, the melting point of lead.

5. The amplitude dependence study of damping with the PUCOT indicated that the break away effect for dislocations was temperature dependent with a maximum break away stress of over 2 MPa near 270°C. This temperature was close to that observed by Youssef for the short-range ordering of Cu-Zn alloys.

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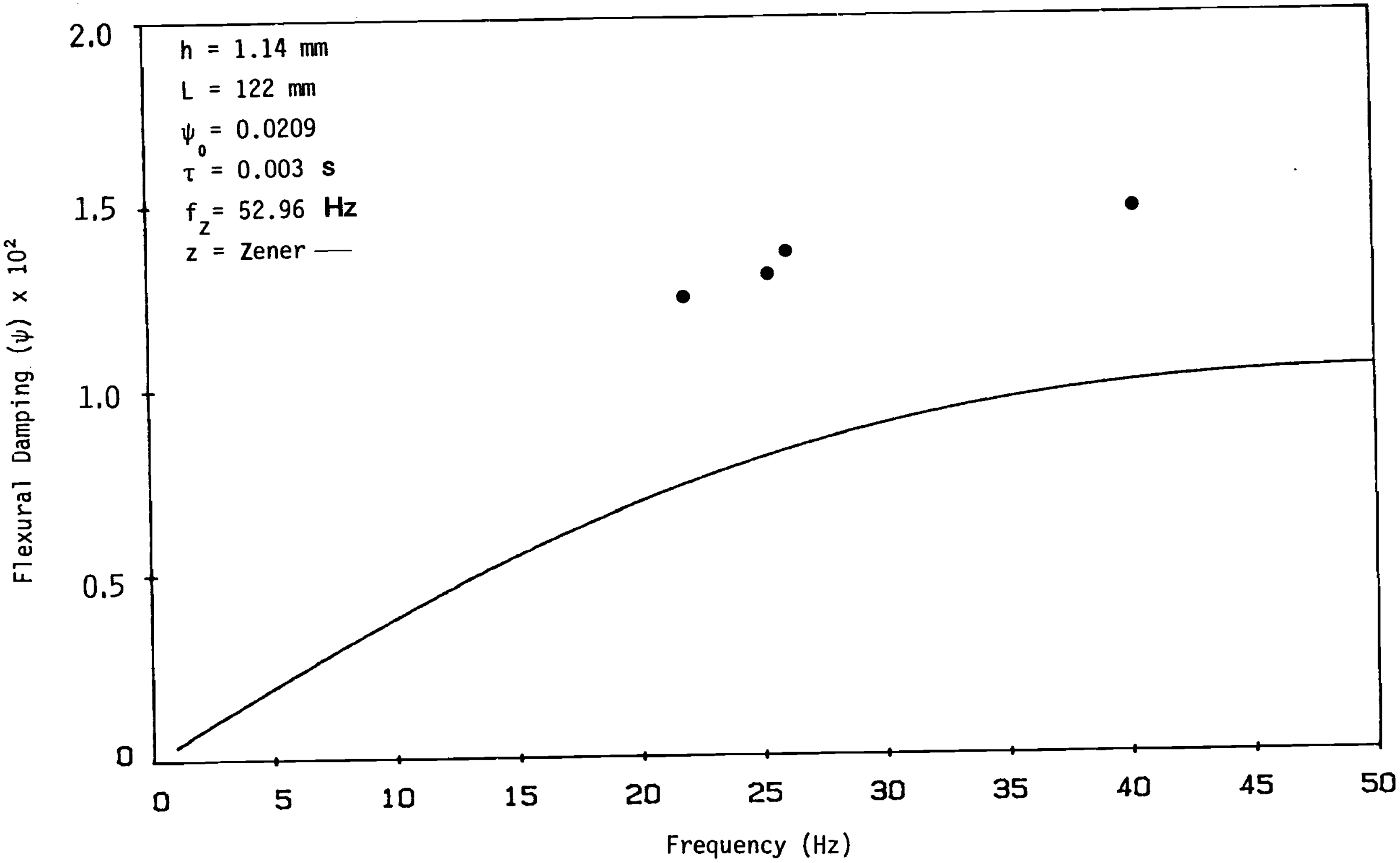

Fig. 1 - Flexural damping versus frequency for brass/2.65% lead as measured by the CB technique.

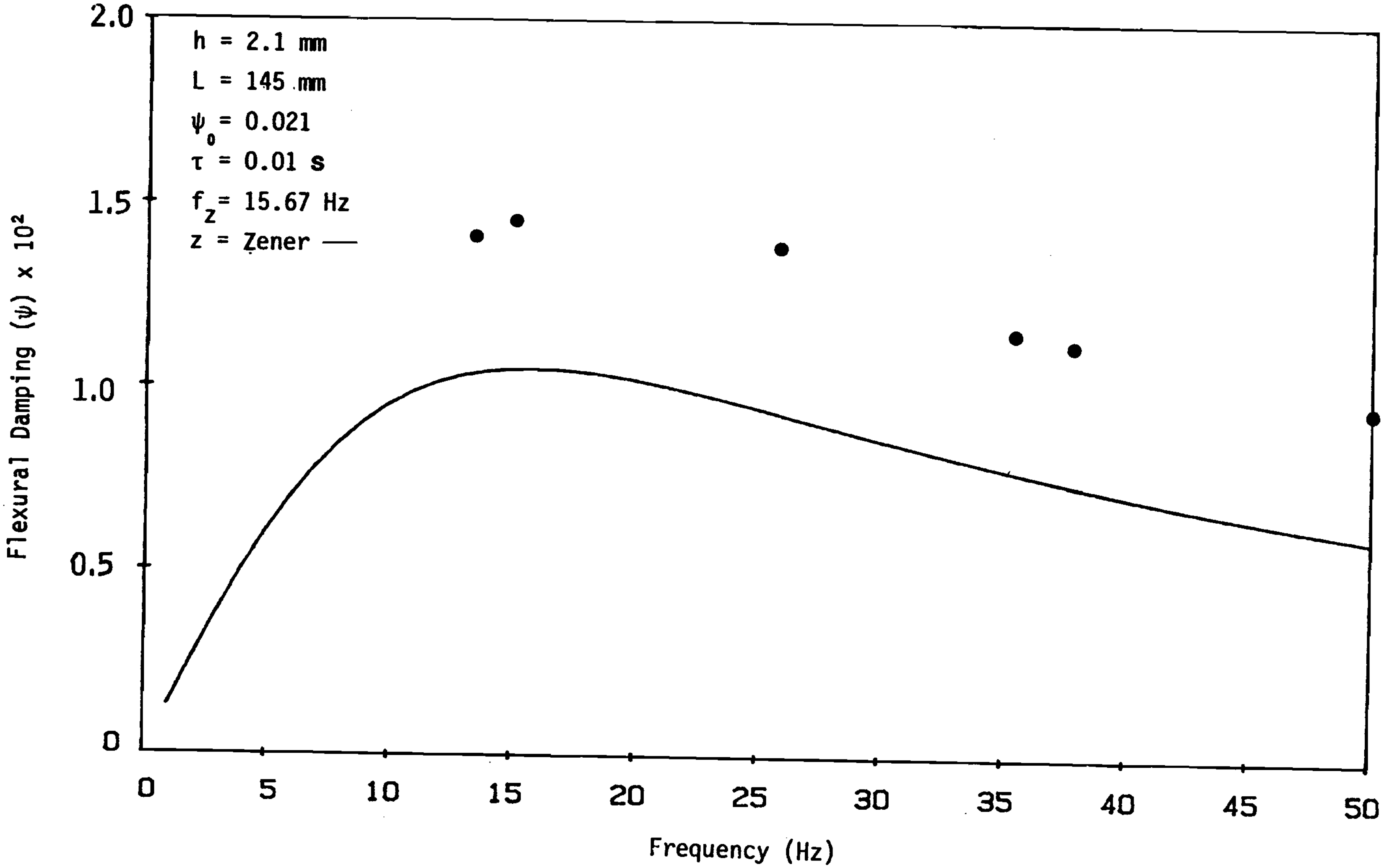

Fig. 2 - Flexural damping versus frequency for lead-free brass as measured by the CB technique.

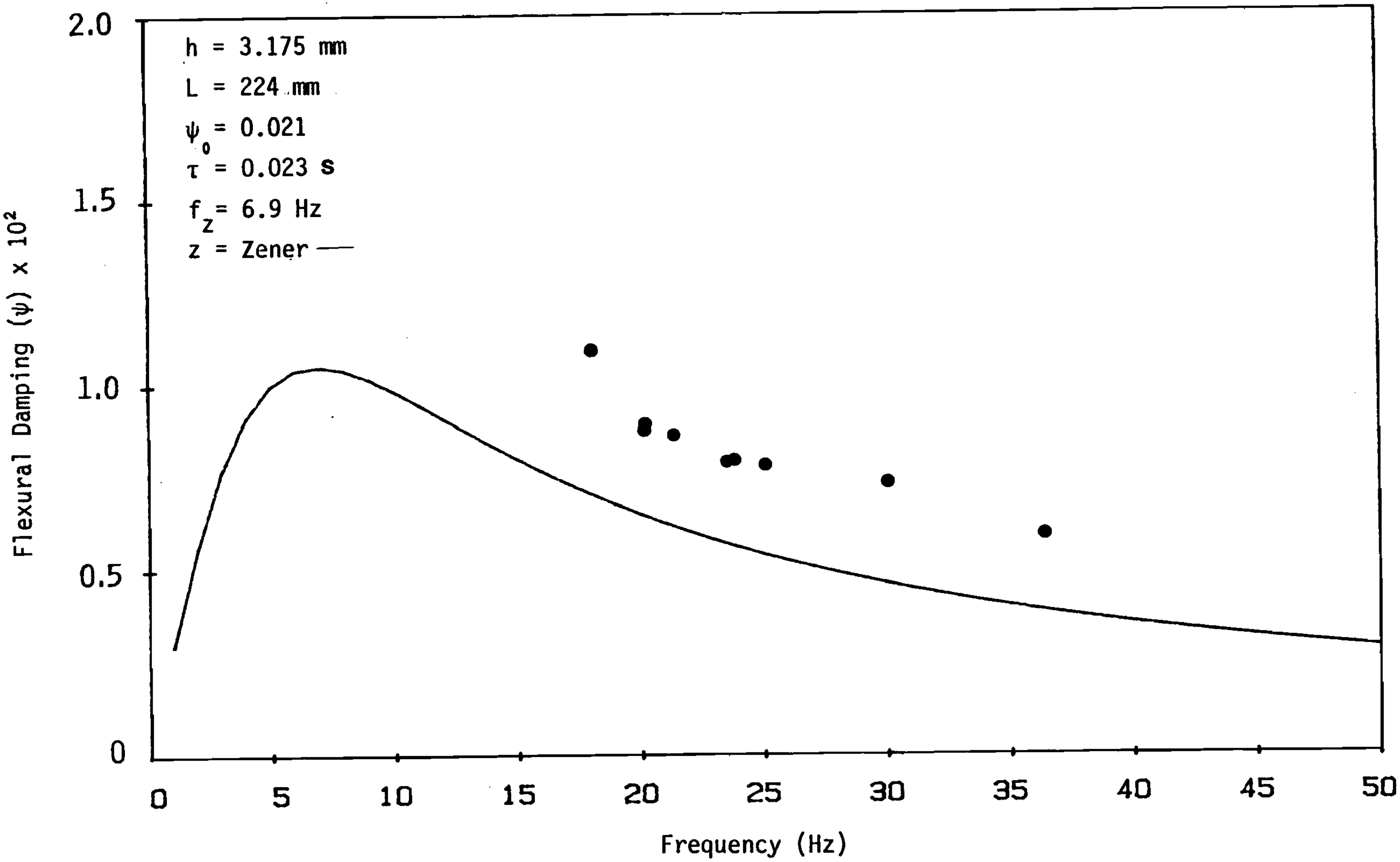

Fig. 3 - Flexural damping versus frequency for lead-free brass as measured by the CB technique.

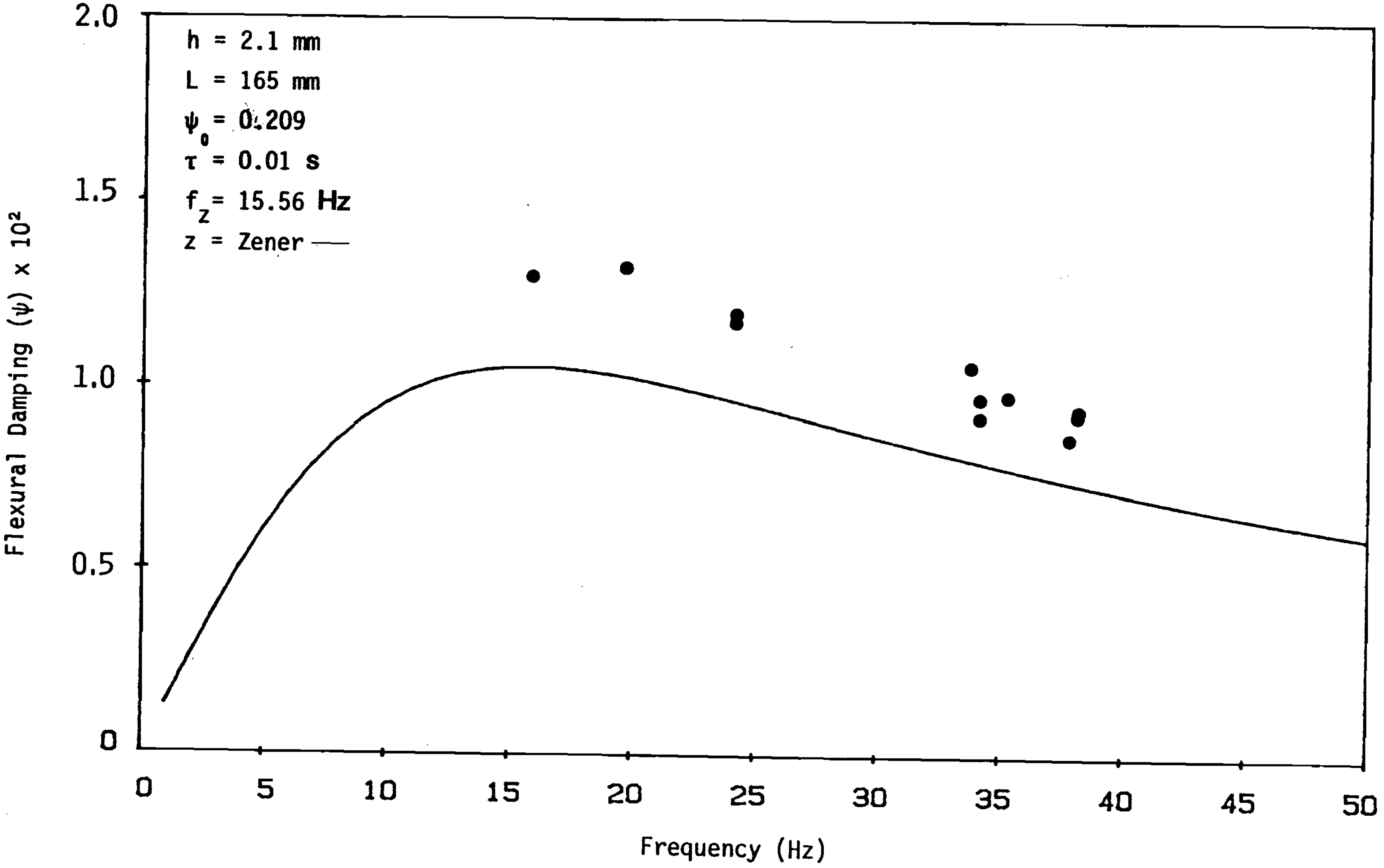

Fig. 4 - Flexural damping versus frequency for brass/2.65% lead as measured by the CB technique.

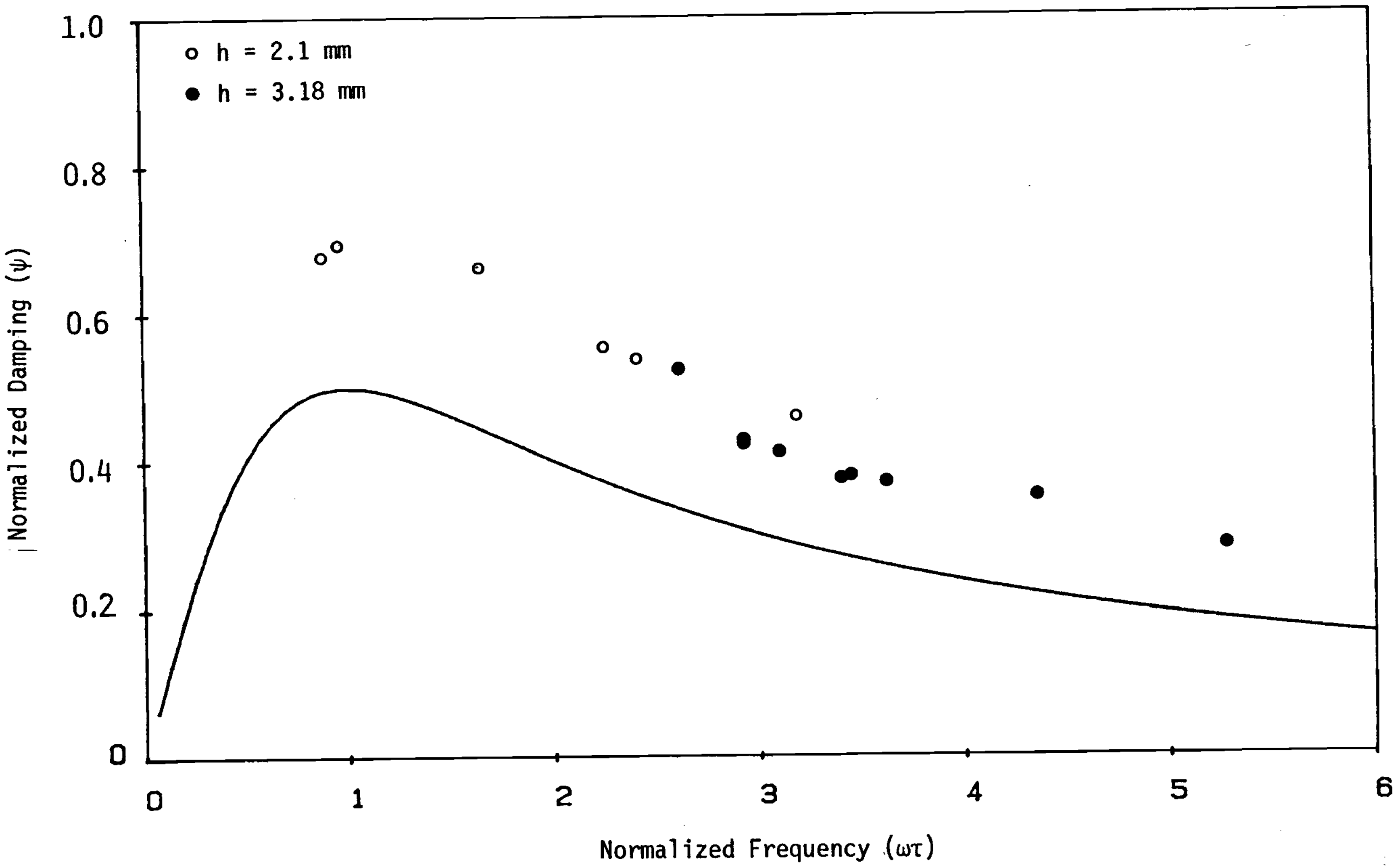

Fig. 5 - Normalized flexural damping versus normalized frequency for lead-free brass as measured by the CB technique.

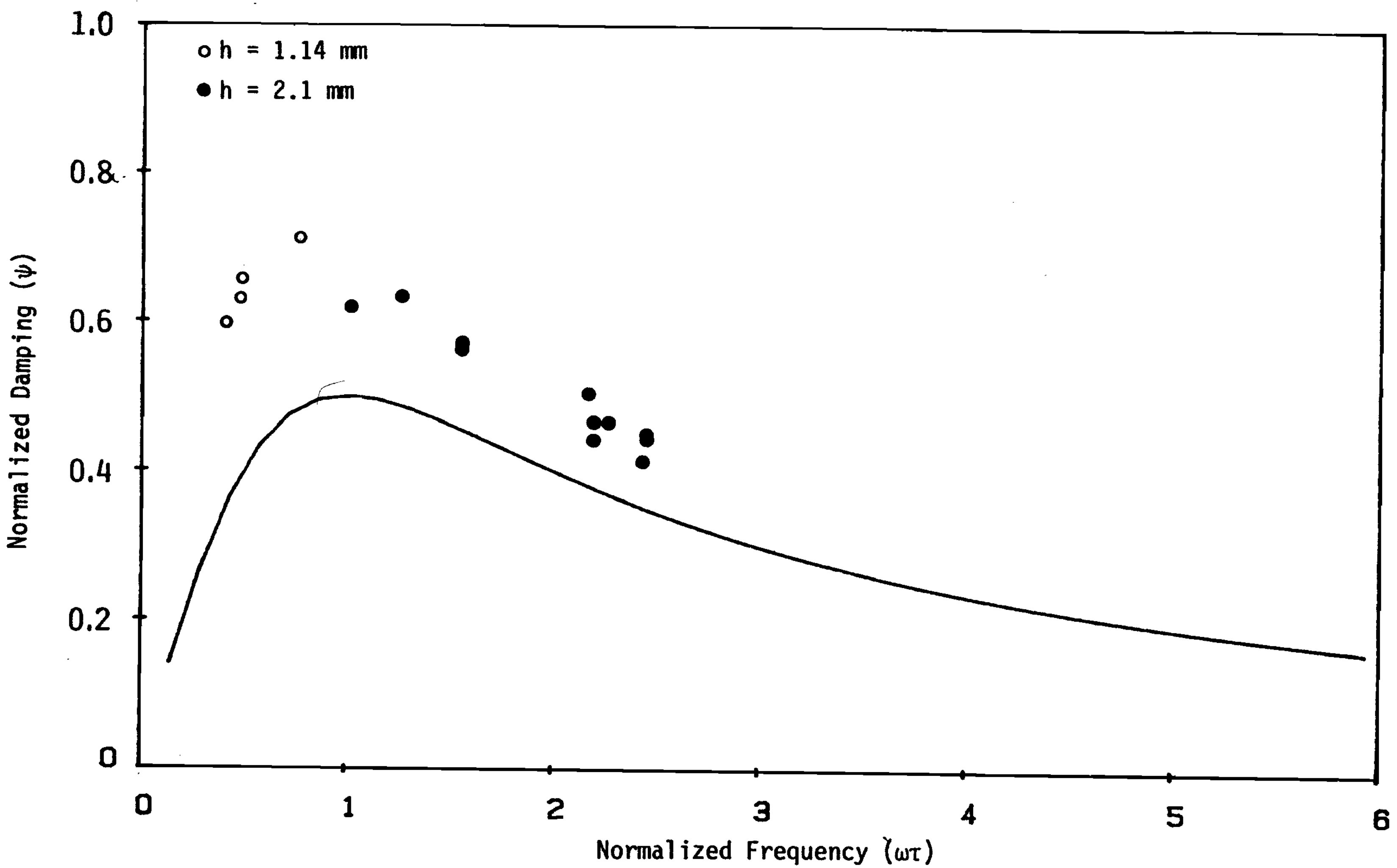

Fig. 6 - Normalized flexural damping versus normalized frequency for brass/2.65% lead as measured by the CB technique.

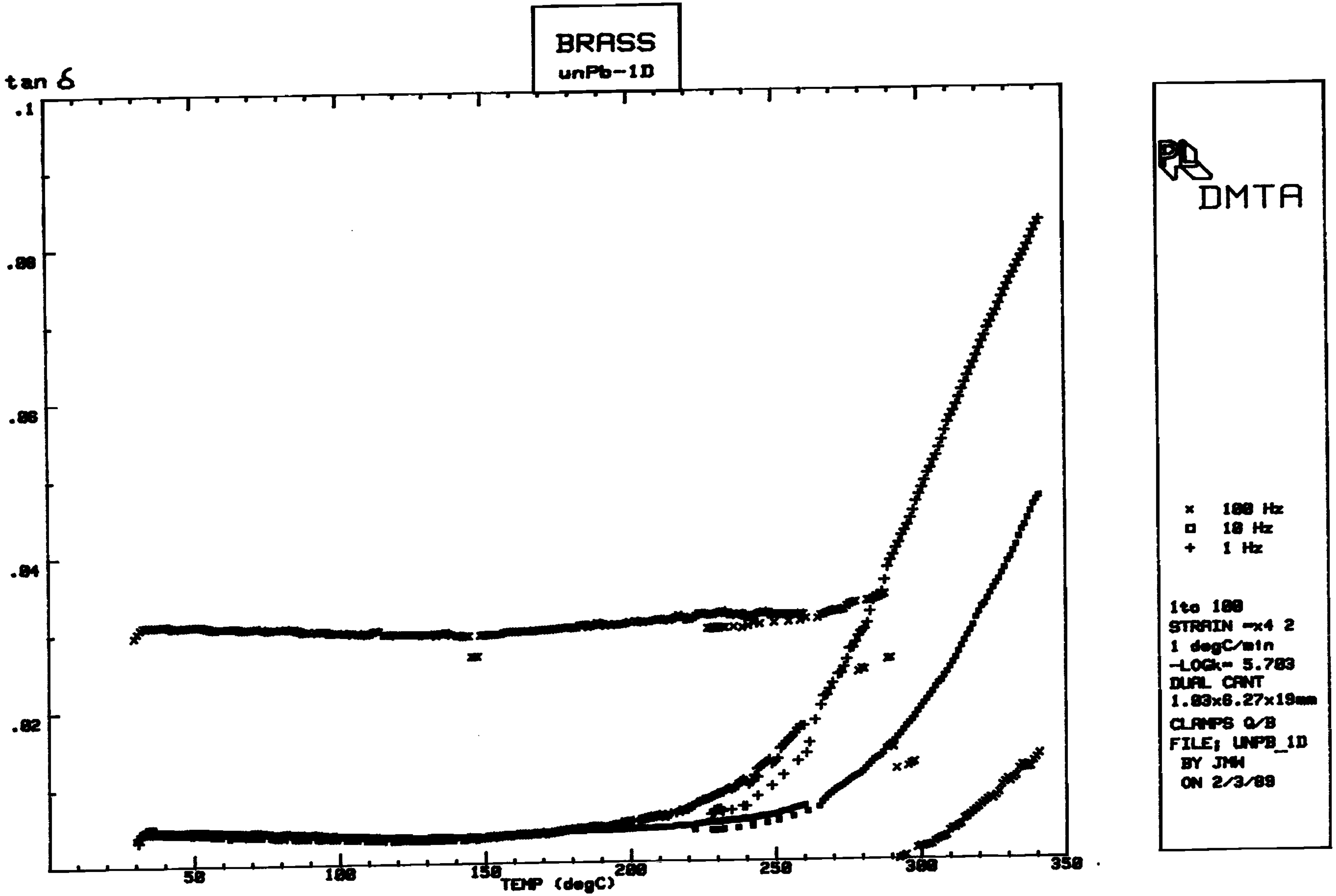

Fig. 7 - Damping as a function of temperature for lead-free brass as measured by the DMTA. The different curves are for different frequencies.

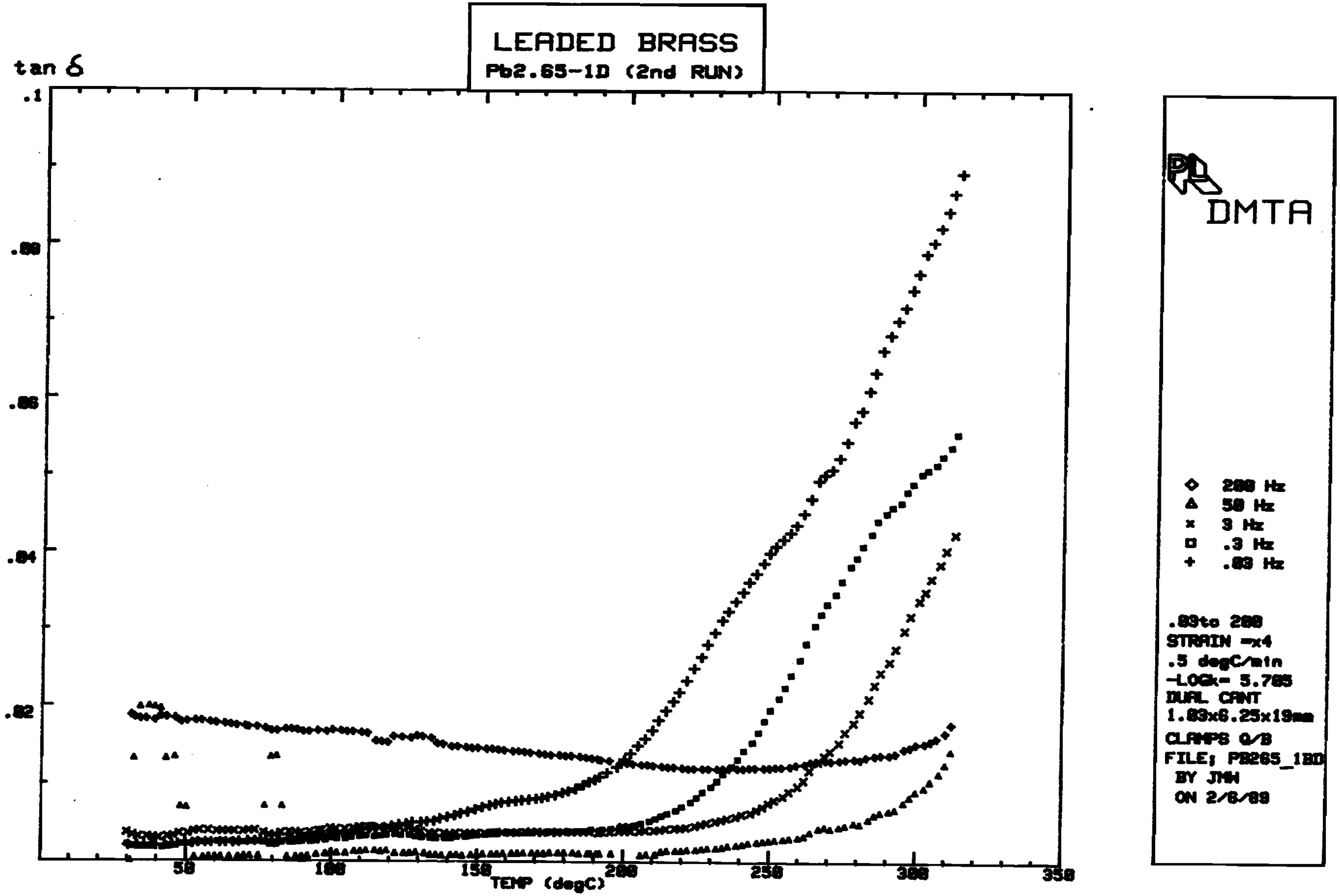

Fig. 8 - Damping as a function of temperature for leaded brass as measured by the DMTA. The different curves are for different frequencies.

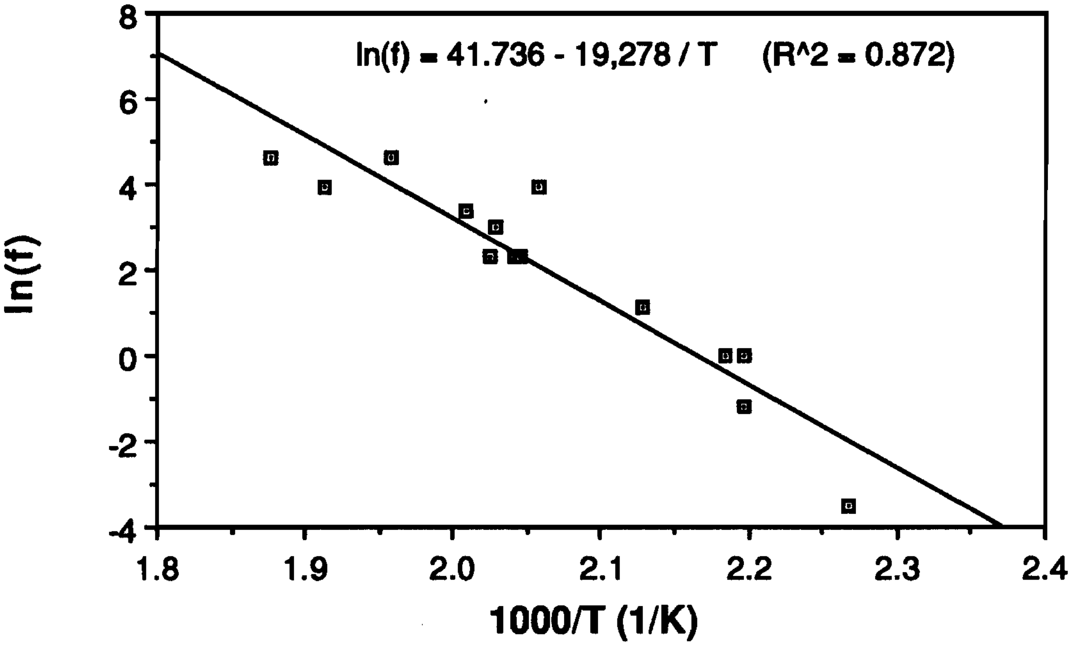

Fig. 9 - Arrhenius plot of the logarithm of the test frequency versus reciprocal temperature for lead-free brass and leaded brass as measured by the DMTA. The data points correspond to the activation temperatures where there was a rise in damping as shown in Figs. 7 and 8.

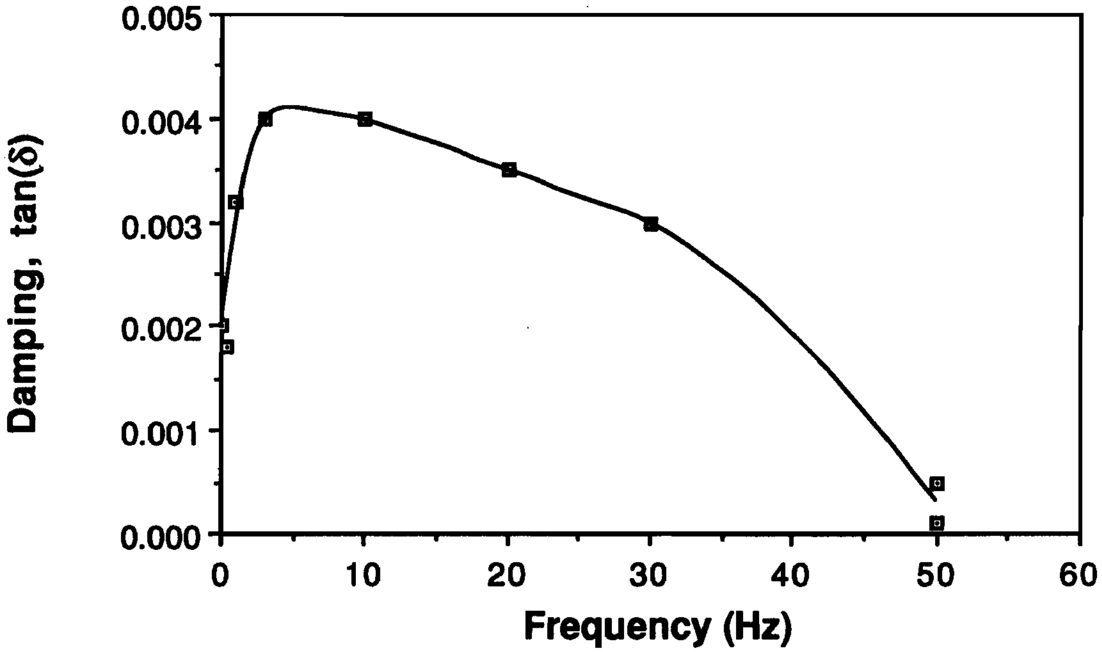

Fig. 10 - Damping as a function of frequency for leaded brass at 30°C as measured by the DMTA.

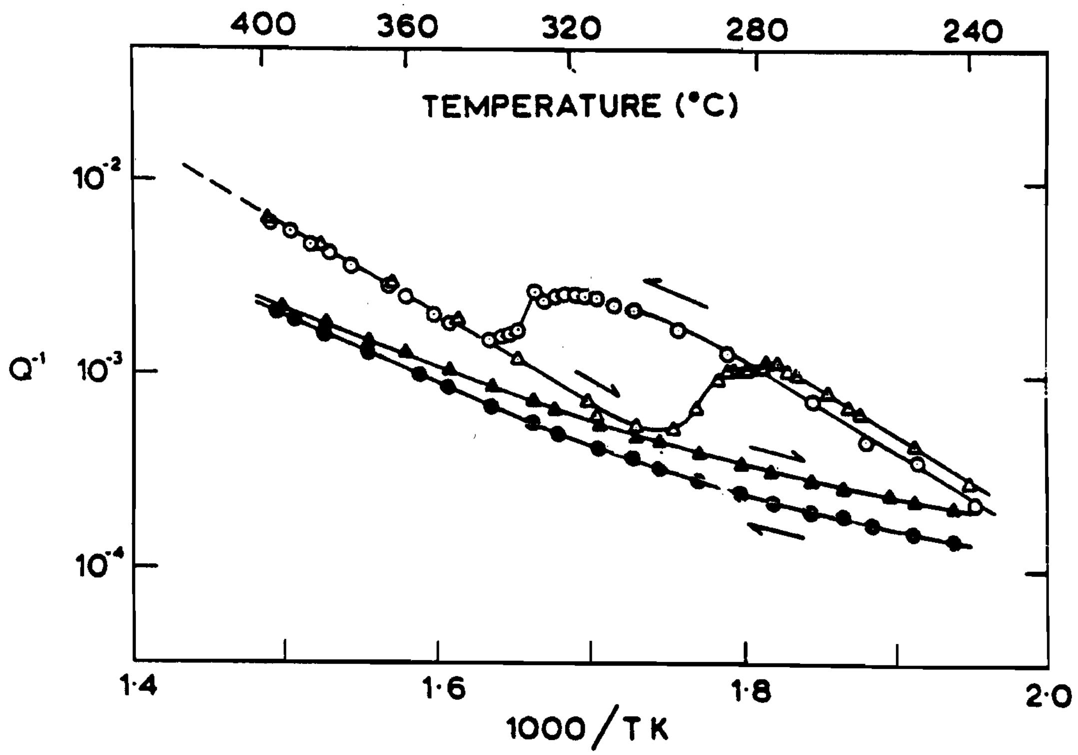

Fig. 11 - An Arrhenius plot of the mechanical damping of leaded (open data points) and lead-free (filled data points) brass as measured by the PUCOT at 40 kHz and at a maximum strain amplitude of 10^{-7}. (From [4].)

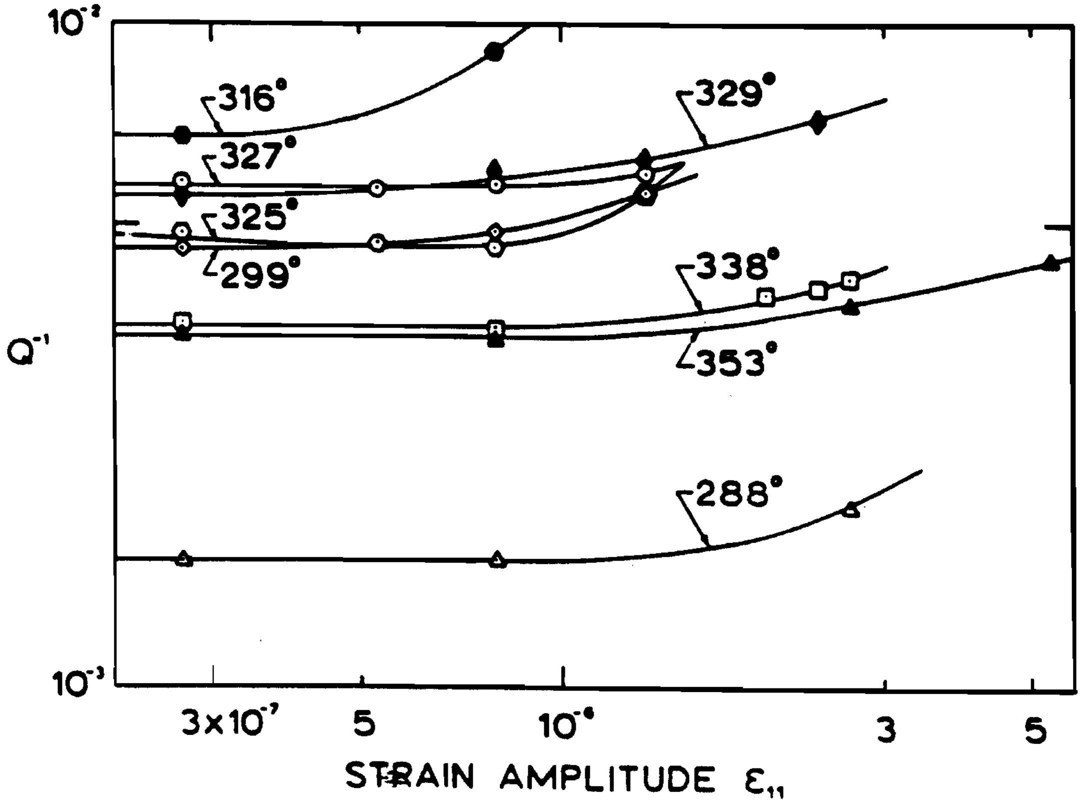

Fig. 12 - Amplitude dependence of the mechanical damping of leaded brass at various temperatures as measured by the PUCOT at 40 kHz. (From [4].)

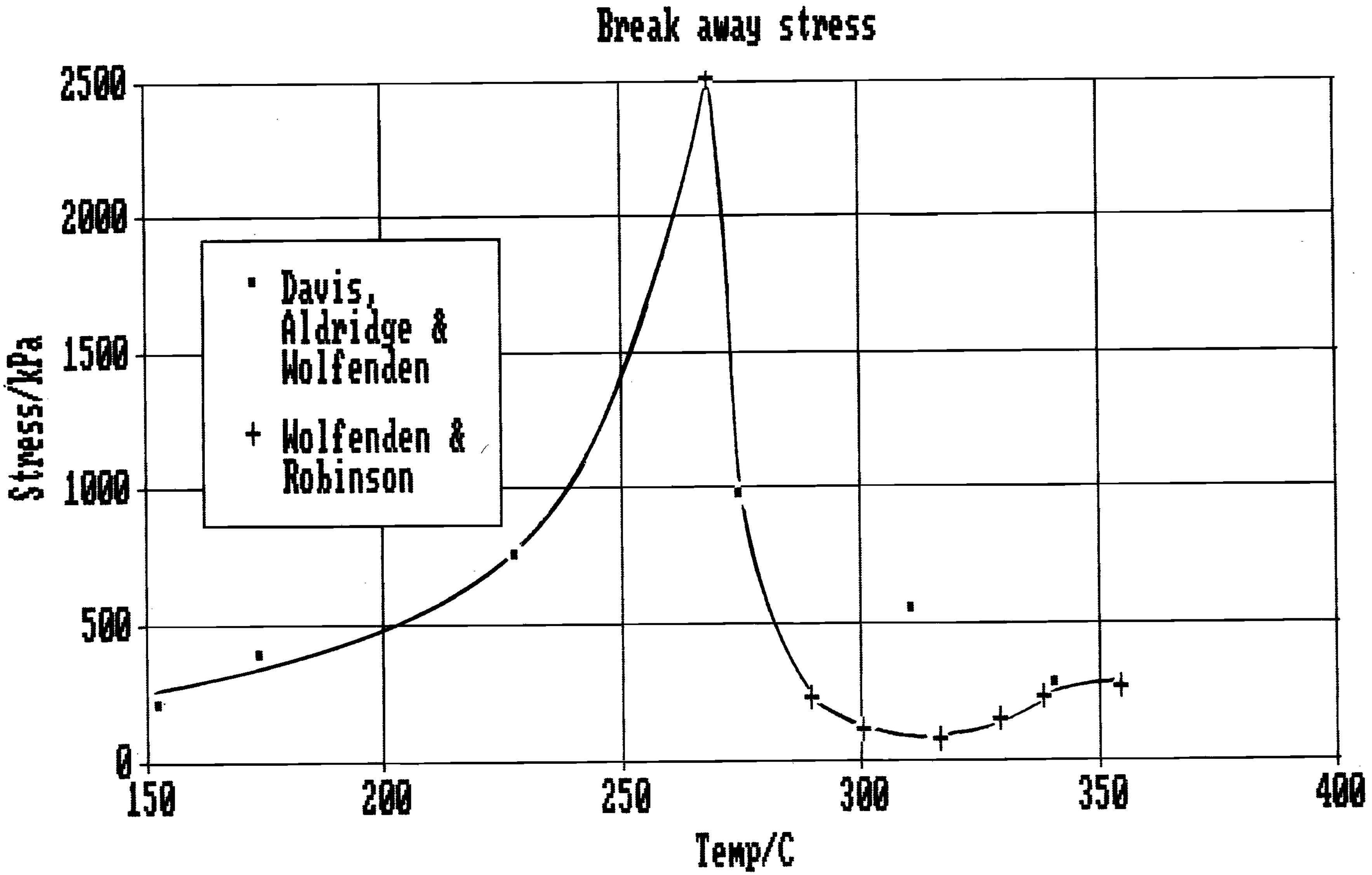

Fig. 13 - Stress required to cause break away of dislocation lines from pinning points as a function of temperature for leaded brass. Earlier data from Wolfenden and Robinson [4] are also shown.

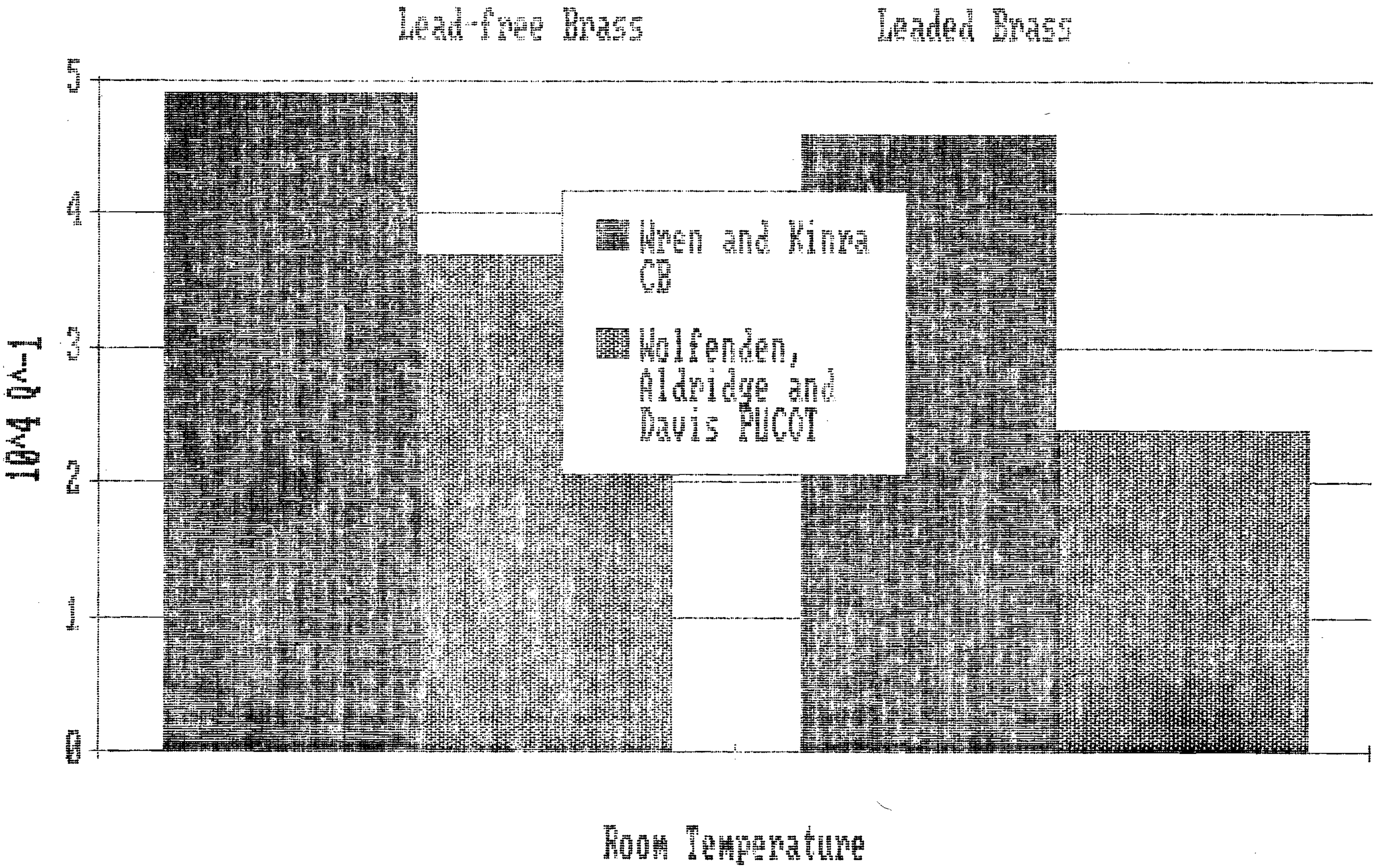

Fig. 14 - A comparison of the damping data as measured by the CB and PUCOT for lead-free and leaded brass tested at room temperature.