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# Viscoelastic tensile and shear properties of the 62 wt% Sn–36 wt% Pb–2 wt% Ag solder alloy

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In this paper the results of the experimental determination of the viscoelastic tensile and shear properties of the eutectic 62 wt% Sn–36 wt% Pb–2 wt% Ag solder alloy in the temperature range between −20 and 100 °C are presented. The dynamic tensile and shear moduli and the viscous damping coefficients were measured using a phase-sensitive resonance technique. The results show that the temperature dependence of the dynamic Young's and shear moduli can be approximated by linear functions and a quadratic polynomial can be used to define a lower bound of the temperature dependence of the viscous damping coefficients of the material. For a temperature rise from 20 to 65 °C the dynamic Young's and shear moduli decrease by approximately 6% and the damping coefficient increases by approximately 80%. © *1998 Chapman & Hall*

## 1. Introduction

Solder alloys are and certainly will remain the major bonding materials in electronic devices owing to the unique combination of favourable electrical, mechanical and processing properties. The incredibly increasing densities of integrated circuits and on printed-circuit boards require demanding packaging technologies, such as fine-pitch surface mount technology (SMT), which result in extremely small solder joints (see, for example, [1–5]). Consequently, the strains within the solder layers are very large, since the thickness of the joints may be less than 30 μm. In these applications the mechanical reliability of the solder joints has become a dominating factor of the expected mean life time of the device (see, for example, [3–7]).

The experimental determination of reliable lifetime estimations using accelerated experiments (see, for example, [8, 9]) or extrapolating conventional test results (see, for example, [1, 10]) are questionable owing to the highly non-linear character of the deformation and damage mechanisms involved (see, for example, [3, 5, 7, 11]). Therefore, much effort has been made recently to develop numerical tools which can be used to simulate the low-cycle thermal fatigue behaviour of soldered joints (see, for example, [3–7, 12]). In all numerical studies, accurate knowledge of the temperature- and strain-rate-dependent material properties of the constituents is a basic requirement to ascertain reliable simulation results. This is especially true for large-strain/large-deformation calculations which use an iterative solution procedure to determine the "exact" stress and strain fields for each new load increment.

For materials which show strong time-dependent behaviour such as solder alloys, the determination of material properties by means of quasistatic testing is difficult. The measured specimen response will always be a combination of the time-independent instantaneous material behaviour and time-dependent creep or relaxation processes which may largely depend on the loading rate and temperature of the test. One possibility for differentiating between time-independent and time-dependent material response components is to use dynamic measurement techniques (see, for example, [13, 14]).

This paper reports the temperature dependence of the viscoelastic tensile and shear properties of the eutectic 62 wt% Sn–36 wt% Pb–2 wt% Ag solder alloy in a temperature range between −20 and 100 °C. The dynamic tensile and shear moduli and the viscous damping coefficients are determined using a phase-sensitive resonance technique analysing the vibration behaviour of cylindrical rods.

## 2. Methodology

Analysing the resonance behaviour of forced vibrations of a material sample is one possibility for determining the elastic and viscoelastic properties of a solid (see, for example, [13–15]).

In the present investigation the phase difference between a sinusoidal excitation signal and the longitudinal or torsional vibration response of a cylindrical specimen is used to determine the dynamic elasticity moduli and the internal damping coefficients of the material.

In the case of small viscous damping which holds for most engineering materials, the complex Young's modulus, $E^*$, and shear modulus, $G^*$, can be approximated as

$$\begin{aligned} E^* &\approx E_0(1 + \mathrm{i}\varphi_E) \\ G^* &\approx G_0(1 + \mathrm{i}\varphi_G) \end{aligned} \qquad (1)$$

where $E_0$ and $G_0$ are the elastic and storage moduli, respectively, and $\varphi_E$ and $\varphi_G$ are the viscous damping coefficients of the material for tensile and shear loading, respectively.

The dynamic Young's and shear moduli can be determined from the resonance frequency $f_n$ of the $n$th vibration mode using

$$c_m = \frac{2L}{n} f_n \qquad (2)$$

where $L$ is the length of the rod and $c_m$ is either the velocity of longitudinal waves in a rod in the case of longitudinal vibrations, i.e., $c_m = c_0 = (E/\rho)^{0.5}$ ($E$ is the dynamic Young's modulus and $\rho$ is the density of the material) or the velocity of shear waves in the case of torsional vibrations, i.e., $c_m = c_2 = (G/\rho)^{0.5}$ ($G$ is the dynamic shear modulus).

It can be shown that the viscous damping coefficients are indirectly proportional to the slope of the phase curve at the resonance frequencies (see, for example, [15]):

$$\varphi_\alpha = -\frac{2}{(\mathrm{d}\Theta/\mathrm{d}f)|_{f=f_n} f_n} \quad (\alpha = E, G) \qquad (3)$$

In Equation 3, $\Theta$ is the phase difference between the excitation signal and the specimen response.

The analytical relations in Equations 2 and 3 must be modified to include the finite mass of the piezoelectric transducers bonded to the specimens, the second-order vibration effects such as lateral or warping deformations, the temperature dependences of the length and density of the specimens if measurements at different temperatures are performed and the possible phase changes introduced by mechanical or electrical components in the measurement chain.

## 3. Measurement system

Fig. 1 shows a sketch of the measurement system used in the current investigation.

Standard and in-house-built piezoceramic transducers were bonded to the cylindrical specimens using on the one hand a fast-curing epoxy resin (Permabond E01) and on the other a cyanacrylate adhesive (Permabond C2). These electromechanical converters were used as source and detector in the longitudinal and torsional vibration experiments. The LeCroy 9420 transient recorder was capable to determine the phase difference between the excitation and the response signal by allowing on-line fast Fourier transformation of the time signals. The LabView™ software package was used to control the measurement system by general-purpose interface bus communication and to analyse the experimental data.

The details and results of extended validation experiments and parameter studies at room temperature have been reported in [16]. From these experimental results it is estimated that the present measurement technique allows for the determination of the storage moduli and the viscous damping coefficients with an accuracy better than 2% and 7%, respectively.

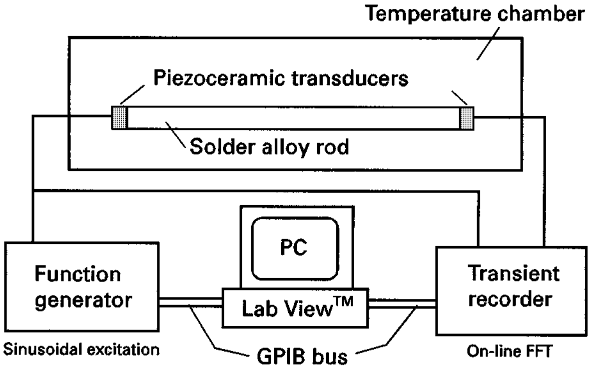

*Figure 1* Sketch of the measurement system. PC, personal computer; GPIB, general-purpose interface bus; FFT, Fast Fourier transform.

The influence of low and high temperatures on the accuracy of the measured viscoelastic material properties has not yet been fully clarified. The experimental results given below show that for two different measurement configurations the deviations in the material characteristics at different temperatures are less than the above-mentioned accuracy estimations. This is a strong indication that the influence of experimental parameters such as specimen support system and bonding techniques remains of the same order of magnitude over the entire temperature range.

## 4. Specimens and experiments

The eutectic 62 wt% Sn–36 wt% Pb–2 wt% Ag solder alloy is the most commonly used solder for electrical interconnects in electronic packages manufactured by SMT. Two solder rods were fabricated by controlled solidification in cylindrical chemical test-tubes. After fabrication, both rods were checked for voids using an X-ray microfocus tube and approximately 30 mm on each side were cut off to exclude end inhomogenities and to produce flat end surfaces which were perpendicular to the axes of the rods. The lengths, $L$, of the rods were approximately 250 mm, the diameters, $d$ were 10 mm and the density, $\rho$, was determined to be 8345 kg m$^{-3}$ for both specimens.

Longitudinal vibrations were excited in both rods using the two different bonding techniques mentioned above. Torsional vibrations were excited in one rod using cyanacrylate bonding. The test temperature was varied between room temperature (RT) and 100 °C in the case of epoxy bonding and between − 20 and 100 °C in the case of the cyanacrylate adhesive.

Only the first few vibration modes were considered in the measurements, since the measured viscoelastic properties were intended to be used in numerical simulations of the low-cycle thermal fatigue behaviour of soldered joints. Therefore, the smallest wavelength was more than ten times the diameter of the rods in the case of the longitudinal vibrations and more than seven times in the case of the torsional vibrations. Thus, no corrections for second-order vibration effects were included in the analysis.

## 5. Results and discussion

The results of the longitudinal vibration experiments are presented in Fig. 2.

As indicated, the data points are the mean values of the measured dynamic Young's moduli of the first few vibration modes. The entire set of all experimental data points has been given in [16].

The experimental results show that the temperature dependence of the dynamic Young's modulus in the temperature range $0\,^{\circ}\mathrm{C} < \vartheta < 100\,^{\circ}\mathrm{C}$ can be approximated by a linear function:

$$E(\vartheta) = -0.055\,\vartheta + 41.90(\mathrm{GPa}) \tag{4}$$

Between RT and 60 °C which is a typical temperature difference that solder joints experience in modern electronic devices, Young's modulus decreases by approximately 6%.

The experimental results suggest that the vibration system using a cyanacrylate adhesive for bonding acts slightly more stiffly than the system using an epoxy resin. This effect is probably the result of the lower glass transition temperature of the epoxy resin on the one side and the thinner bonding layers which result using a low-viscosity cyanacrylate adhesive on the other.

The results for the dynamic shear modulus as a function of temperature are summarized in Fig. 3.

The linear least-squares approximation for the shear modulus in the temperature range $0\,^{\circ}\mathrm{C} < \vartheta < 100\,^{\circ}\mathrm{C}$ is

$$G(\vartheta) = -0.022\,\vartheta + 15.16(\mathrm{GPa}) \tag{5}$$

The shear modulus decreases by approximately 6% between RT and 60 °C.

From the two independently measured elasticity constants, $E(\vartheta)$ and $G(\vartheta)$, Poisson's ratio, ν, can be calculated using the linear elastic relation

$$\nu = \frac{E}{2G} - 1 \tag{6}$$

The result of ν as a function of temperature is shown in Fig. 4.

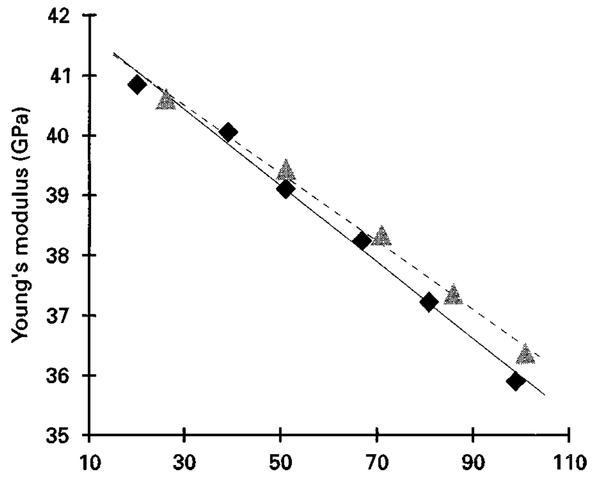

*Figure 2* Measured dynamic Young's modulus versus temperature. (◆), rod 1, mean values, $n = 1$–$5$; (▲), rod 2, mean values, $n = 2$–$5$; (——), rod 1, linear regression; (– – –), rod 2 linear regression.

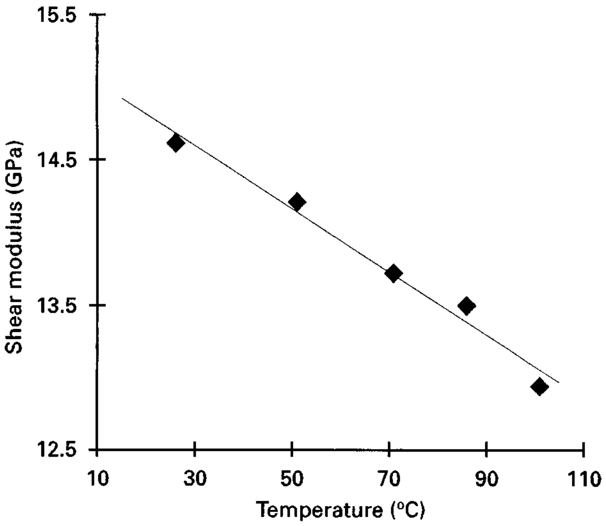

*Figure 3* Measured dynamic shear modulus versus temperature. (◆), rod 1, mean values, $n = 3$–$7$; (——), rod 1, linear regression.

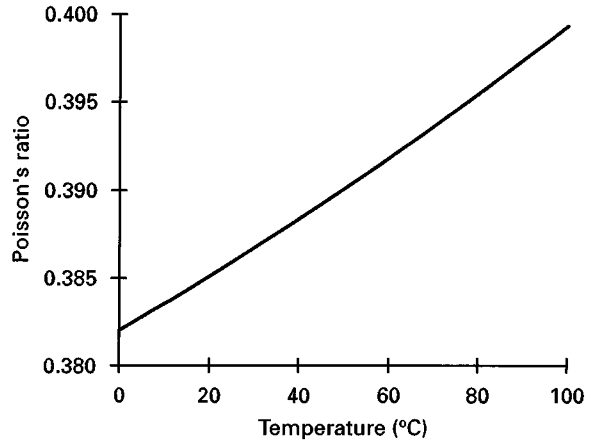

*Figure 4* Calculated Poisson's ratio versus temperature.

The ν value of about 0.385 at RT as well as the calculated temperature dependence confirmed expectations which were based on material data of tin and of tin alloys given in the literature (see, for example, [2, 11, 17]). Thus, the accuracy of the independently measured dynamic Young's and shear moduli seems to be very good.

Fig. 5 shows the results for the damping coefficients determined from the slopes of the phase curves at the resonance frequencies using Equation 3.

The damping coefficients as a function of temperature form a narrow band. The deviations between the individual data points at a specific temperature are determined by two physical effects. Firstly, the damping coefficient in tension and shear are not identical although normally only one viscoelastic damping coefficient or $Q$-factor is given for a specific material (see, for example, [13, 17, 18]). The viscous damping coefficient for shear loading is higher than for tensile loading and the experimental data show that the deviation between the averaged damping coefficients is approximately 0.002. Secondly, the damping coefficient is slightly higher for low frequencies than for higher frequencies or vibration modes. The highest

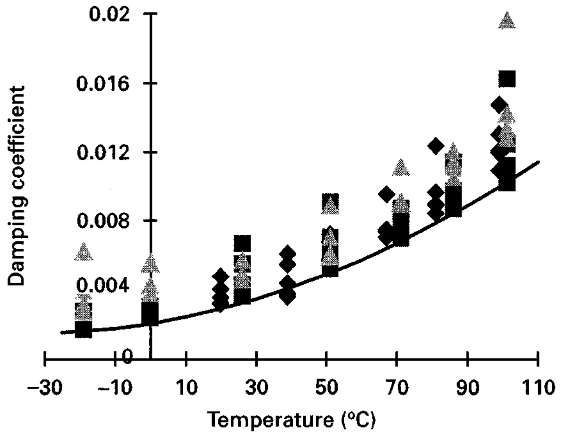

*Figure 5* Measured damping coefficients versus temperature. (◆), rod 1, longitudinal; (■), rod 2, longitudinal; (▲), rod 1, torsional; (——), quadratic lower-bound approximation.

damping coefficient of an individual set of data points at a specific temperature always refers to the lowest vibration mode.

The quadratic function given in Equation 7 is a lower-bound approximation of the temperature dependence of the viscous damping coefficient $\varphi$ of the solder alloy in a temperature range $-20\,^{\circ}\mathrm{C} < \vartheta < 100\,^{\circ}\mathrm{C}$:

$$\varphi(\vartheta) = 4.81 \times 10^{-7}\vartheta^{2} + 3.28 \times 10^{-5}\vartheta + 2.09 \times 10^{-3} \qquad (7)$$

For a temperature rise from RT to 60 °C the damping coefficient increases by approximately 80%.

## 6. Conclusions

The determination of the viscoelastic properties of the 62 wt % Sn–36 wt % Pb–2 wt % Ag solder alloy as a function of temperature has shown the following.

1. In a temperature range between 0 and 100 °C, the temperature dependence of the storage moduli in tension and shear can be approximated by linear functions.
2. A lower bound of the viscous damping coefficient in tensile and shear loading as a function of temperature can be approximated by a quadratic polynomial.
3. The dynamic Young's and shear moduli decrease by approximately 6% and the viscous damping coefficient increases by approximately 80% for a temperature rise from RT to 60 °C.

Further investigations are needed to clarify whether or not the viscoelastic properties of the bulk material are representative of soldered joints with solder layers of thickness a few micrometres [11]. Additionally, further studies are necessary to quantify the contribution of each individual component in the measurement chain to the total phase difference over the entire temperature range.

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