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THERMAL CONDUCTIVITY OF MOLTEN LEAD FREE SOLDERS

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Abstract: The increasing influence of computational modelling in all technological processes generates an increased demand for accurate values of the physical properties of the materials involved, which are used as fundamental inputs for every model.

In the production of electronic circuits, a thorough knowledge of the thermal conductivity of molten solders can result in a better controlled soldering process. As a result, this information can be used for setting the optimum soldering profile and thereby lead to improvement in the quality control of the solder joints.

This paper describes the principles of the experimental technique employed for the measurement of the thermal conductivity of molten solders and describes the essential features of the instrumentation. The values of the thermal conductivity of different lead and lead-free solder compositions, measured at various temperatures and temperature profiles, are compared and briefly discussed.

Keywords: Thermal conductivity, molten solder, FE modelling

1. Introduction

With the development of computational software, most of the modern fabrication processes are modelled mathematically before they are implemented in production. In almost every production process, computation is being used to predict the behaviour of the components and materials during manufacturing. The importance of such modelling increases with decreases of the dimensions of components and amounts of materials used and with increasing integration. For meaningful modelling, the material properties must be very accurately defined at specific conditions and for every temperature at which the material is used or a component mounted. However, without knowing the exact mechanical and thermal properties, the mathematical modelling cannot result in accurate design and process solutions. The thermal conductivity is the most important thermal property involved in models of thermal expansion and heat transfer phenomena. For electronic production, soldering and solder solidification belong to the most critical parts of the fabrication process and therefore this paper focuses on the measurement of the thermal conductivity of molten solders.

Since a new lead-free policy was introduced in all industries [1] and particularly in electronics production, the research and development of lead-free soldering materials and processes have become an important issue. Within the last few years, several new lead-free compositions have been introduced, investigated, and tested.

The main goal of this paper is to investigate both lead and lead free solders and observe their thermal conductivity in the liquid phase throughout a range of temperatures above the melting point. Knowing accurate thermal conductivity values for molten solder can significantly help to improve the fabrication process of any electronic device that makes use of them.

A technique with accuracy within the range ±2% has been developed in the last decade [2] and an instrument has been designed to measure the thermal conductivity of molten metals. This same instrument is also used for the current project.

2. Transient hot wire method

Because the main difficulty in performing accurate measurements of the thermal conductivity of fluids lies in the isolation of the conduction process from other mechanisms of heat transfer, it is necessary to employed transient methods. Currently the most accurate transient technique is that based upon a transient hot wire method. The success of transient techniques is based on the fact that the characteristic time for the acceleration of the fluid by buoyancy forces is much longer than the propagation time of a temperature wave originated by a strong and localised temperature gradient. The transient hot wire technique is an absolute technique and instruments based on its principle are considered capable of providing the highest accuracy possible at present [3].

The basic concept of the method is that a voltage step is applied to a 'hot-wire', which is immersed in the fluid, and the resistance of the wire (or the voltage across it) is monitored as a function of time. As the wire is being heated up and its resistance is increasing with temperature, the voltage also increases. From the changes of voltage with respect to time, transient resistance changes and the heat flux within the fluid can be calculated. Assuming that an isotropic fluid has a temperature independent thermal conductivity, density and heat capacity over small temperature ranges, a fundamental equation of all transient experimental methods for the measurement of the thermal conductivity can be written [3, 4]

$$\rho \cdot C_P \cdot \frac{\partial T}{\partial t} = \lambda \cdot \nabla^2 T \tag{1}$$

where ρ is density [kg/m^3], C_p is specific heat capacity [J/kg·K], T is temperature [K], t is time [s] and λ is thermal conductivity [W/m·K]. Eq. (1) also assumes that there is no contribution of radiative transport in the heat transfer.

A solution of the heat transport Eq. (1) for the transient hot wire method can be derived. It defines the temperature rise of the wire which is immersed directly in the fluid and is given by

$$\Delta T = \frac{q}{4\pi\lambda} \ln\left(\frac{4 \cdot \lambda \cdot t}{\rho \cdot C_P \cdot r_0^2 \cdot e^{\gamma}} \right) \tag{2}$$

where q is the heat flux per unit length [W/m], r_0 is the radius of the hot wire [m], γ is Euler's constant (0.57721…).

In its basic form, Eq. (2) indicates that the thermal conductivity of a material surrounding the wire can be derived from the slope of the line relating temperature rise to the logarithm of time. For the circumstances of interest here we must separate the molten metal test fluid from the metallic wire by an electrically insulating material so that Eq. (2)

cannot be used directly for the evaluation of the thermal conductivity of the molten metals, although the basic dependence on the property remains intact. Instead, we employ a finite-element model of the conduction process to replace Eq. (1) and its solution in this more complicated situation.

3. Measuring procedure

The sensor was originally designed and tested during a previous project [2] and is illustrated in Figure 1. The conductive lines are thick-film printed on unfired alumina tapes of thickness 0.3 mm. The 99.99% pure platinum wire (Hot Wire) is placed and sandwiched between two pieces of alumina tape to ensure electrical isolation from the melt. This feature is essential for measurements of electrically conductive liquids but on the other hand it makes the mathematical equation more complicated and subsequently this step disallows using an analytical solution.

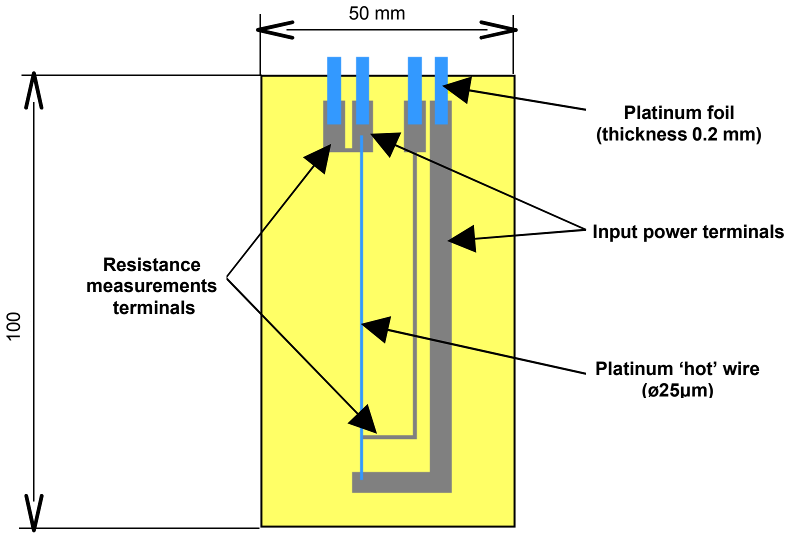

Fig. 1: Sensor (top view before covering wire and thick film pattern with alumina tape)

Experiments have been carried out in a high temperature tubular furnace at temperatures varying from several degrees above the melting point of the solder to approx. 350 ºC. The thermal conductivity is expected not to change significantly within the range considered useful for the electronics industry and therefore it is sufficient to run measurements just at four different temperatures equally distributed from the melting point to 350 ºC.

The resistance-time response (within one second after applying power to the wire) is measured using two data acquisition cards with different sampling rates monitoring the out-of balance signal from a highly accurate resistance bridge. Firstly, the change in resistance is derived and knowing the temperature coefficients of resistance the changes of temperature of the wire with respect to time can be calculated.

The average amount of heat flow per meter length is also calculated and it is used as an input for the finite element analysis for deriving the thermal conductivity of the measured liquid. For the mathematical finite element modelling, a 2D model of the cross-section has been designed and can be seen in Fig. 2. This model is an enhanced version of the previous finite element model used [5].

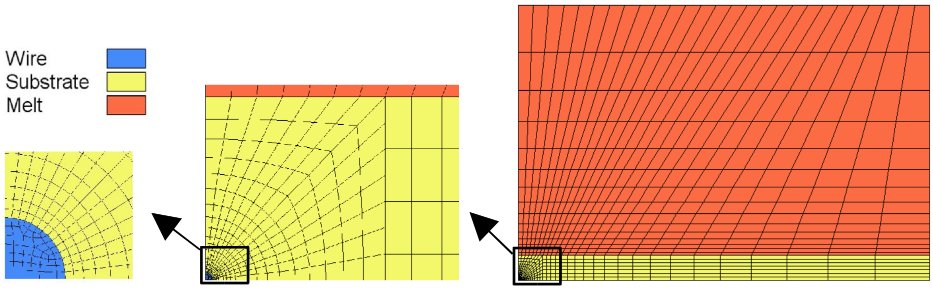

Fig. 2: Meshed 2D model of the cross-section of the sensor and melt

4. Lead vs. lead-free solders

The thermal conductivity of two tin/lead and two lead free solders have been measured and a summary of the solders with their most important thermal properties is given in Table 1.

	Sn60Pb40	Sn62Pb36Ag2	Sn99.3Cu0.7	Sn95.5Ag3.8Cu0.7
Density [kg/m^3]	8520	8440	7320	7405
Specific heat [J/kg·K]	172	N/A	220.5	220.7
Thermal conductivity [W/m·K]	56.6	N/A	65.73	60.32

Table 1: Material properties of solders in solid state [6,7]

Based on the properties of the solders mentioned above and knowing the thermal conductivity of pure tin, which was published in earlier works [2,8] , it is possible to predict the values of the thermal conductivity for the lead-free solders within ±10%. This fact can be also used as a validation of the model and experiment setup.

The thermal conductivity of all the solders is derived from a comparison of the temperature rise obtained from measurements and the temperature rise calculated using FEM software. To obtain the most accurate result, the temperature derived from modelling should ideally match the experimental results.

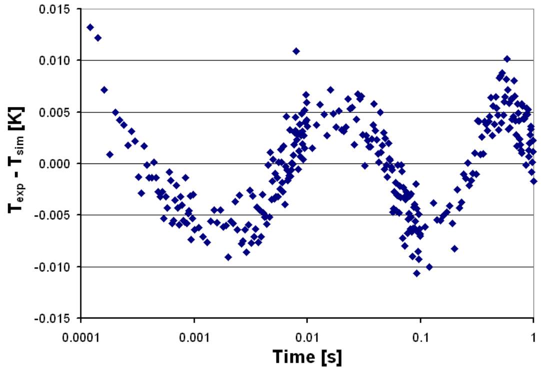

Fig. 3: Comparison between the experiment and output of the FEA

Fig. 3 illustrates the difference between the model and the experiment for the present analysis. The total temperature rise of the wire in the experiment is about 7 K so that a deviation of 0.01 K is equivalent to approximately 0.15% of the temperature of the wire after 1s from power input. The input power into the platinum wire is about 5 W.

The thermal conductivity values illustrated in the figures below are averaged values obtained after several analyses of measurements at each temperature. The error bars on the graphs are equivalent to the range ±3% of the current value and show the range of the accuracy of the instrument and method itself.

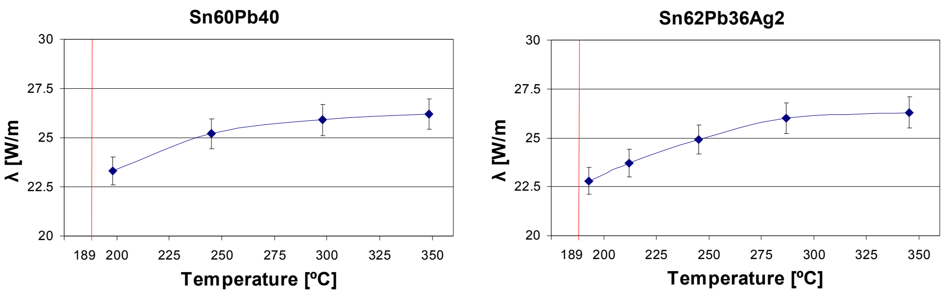

Fig. 4: Thermal conductivity of tin/lead solders (red line shows the upper region of the melting range)

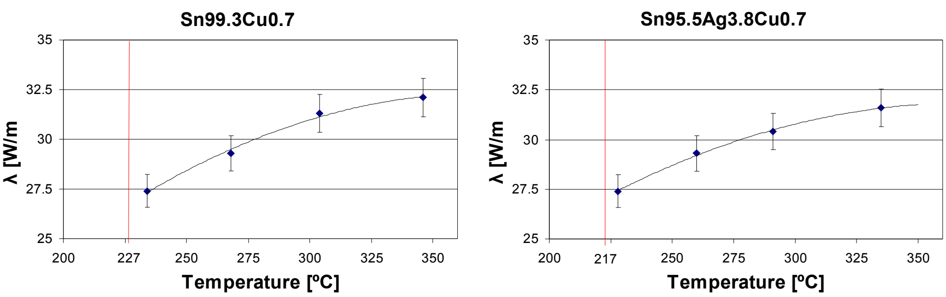

Fig. 5: Thermal conductivity of lead-free solders (red line shows the melting point – eutectic solders)

5. Conclusion

The thermal conductivities of lead-containing and lead-free solders have been analyzed from the view of their thermal properties in the liquid state. The samples containing lead show significantly lower values of thermal conductivity throughout the industrially useful range of temperatures. The differences of the composition containing a small amount of silver are very small and it can be assumed that addition of other metals with concentrations less than 2% has no influence on the overall thermal properties.

The thermal conductivity of lead free solders is very close to the thermal conductivity of pure tin. With addition of other metals (impurities), the thermal conductivity decreases even if the impurity has higher thermal conductivity itself (the same as for solid state). However these changes are very small and are still in the range of accuracy of the technique which is about 3%.

Overall it can be concluded, that the thermal conductivity of molten lead free solders is approximately 5 W/m·K higher than for leaded solders.

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