The thermo-EMFs of tin-lead alloys

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pressure gradient term has an almost negligible effect (which may, however, be estimated if required).

(ii) Consistent results for skin friction are obtained from continuous film tests using different positions of film leading edge and different oil viscosities.

(iii) The oil droplet technique gives results in agreement with the continuous film technique.

(iv) The droplets may be used to estimate small departures from two-dimensional flow.

(v) Development of the oil film profile following a change of skin friction distribution (introduction of the spoiler) is correctly predicted by the characteristics method. Properties of these profiles, such as their envelope and the variation with time of maximum height, are in accord with theory.

9.2 *Vortex generator experiment*

(i) Oil droplets have been successfully used to show the surface streamline pattern in detail.

(ii) The continuous film technique with a number of different leading edge positions has been used to obtain skin friction variation. Even at high air speeds the leading edges of oil films remain free of waves, so this method or the droplet method would still be applicable at high speeds.

(iii) It has been shown that ridges and valleys in the oil film profile act as streamline markers. Similarly, disturbances introduced either accidentally (dust) or deliberately (threads) can be used to show surface streamlines.

(iv) Measurements of y, n and τ along streamlines on which all are varying are entirely consistent with theory.

9.3 *General conclusions*

We believe that the methods described give a wealth of information about skin friction and surface flow which would be extremely difficult if not impossible to obtain by any other means. A good example is provided by the rapid variations in skin friction between the streamlines B, C and D immediately behind the vortex generators. While the general pattern of flow behind vortex generators as shown in figure 8 has been known for many years, the authors believe that these rapid variations, which may indicate the presence of a vortex of opposite sign close to the surface, have not previously been observed.

While it remains desirable to compare these methods with others, we believe that the internal consistency and agreement with theory which has been shown goes a long way towards establishing the methods on a firm basis. The main limitation as to accuracy, particularly in flows involving temperature changes, may well arise from the need to know the viscosity of the oil.

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Abstract The thermo-EMFs of tin–lead alloys in the composition range of 0–100% have been measured against copper for temperature differences of up to 100°C. It was found that there is a dip in the thermo-EMF–composition relationship at 18% tin. The thermo-EMF for SnPb40 alloys used for electronic assembly is 145 μV at 50°C temperature difference between the hot and cold junctions.

1 Introduction

This paper reports an investigation into the thermo-EMF generated between tin–lead (Sn–Pb) alloys and copper. The study was carried out because the thermoelectric (Seebeck) effect of tin–lead alloys used as solder is often of interest in the design of high-sensitivity electronic circuits, e.g. operational amplifiers, where large DC voltage gains are required. Special solders with a low thermo-EMF, such as 75% cadmium–25% tin, have been reported (Charnock 1959) and are used for especially critical purposes, but generally the effect is neglected or simply minimized by stabilizing the temperature of the circuitry as much as possible.

Even though a cadmium–tin solder has low thermo-EMF properties, electronics engineers and circuit designers sometimes require to know the DC voltage generated at joints between the conventional tin–lead solders and copper so that the required design performance can be attained. The production assembly of components onto printed circuit boards is usually carried out using wave soldering techniques (Strauss and Barnes 1956) and tin–lead solders with a tin content between 60% and 64%. Before considering experimental data, it is useful to consider the available information on thermo-EMF generation in solder–copper systems.

The thermo-EMF of a couple depends, amongst other factors, on the logarithm of the ratio of the resistivities of the metals in the couple (Smart and Smart 1963). From this, to minimize the thermo-EMF generated, the resistivities and temperature coefficients of resistivity of the metals used should be as similar as possible. It is known that the resistivities of metals of interest in soldering are in the order: copper, cadmium, tin, lead (table 1) and that tin–lead alloys would probably exhibit a higher thermo-EMF with respect to copper than cadmium–tin alloys. Although the resistivity values are a guide to the thermo-EMF generated, material constants and joint characteristics, such as compound formation (Asanovich *et al* 1969),

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Table 1 The electrical properties of copper and possible solder constituent metals

Metal	Resistivity at 20°C ($\mu\Omega$ cm^{-3})	Coefficient of resistivity (0–100°C) $\times 10^3$
Copper	1·673	4·3
Cadmium	7·4	4·3
Tin	12·8	4·2
Lead	20·6	3·36
Antimony	42·0	5·1
Bismuth	116·0	4·2

also play an important part in determining the actual voltages developed and therefore, to evaluate these factors, the thermo-EMFs of soldered joints made with Pb–Sn alloys containing 0–100% tin have been determined.

2 Experimental

Experimental junctions were made, with a soldering iron, of 16–18 SWG (1·2–1·6 mm) solid solder wires onto 0·015 in × 0·25 in (0·38 mm × 6·4 mm) annealed copper strip using a commercially available active flux. Values of EMF were measured for each solder alloy for temperature differences between 0 and 100°C±0·25°C at 5°C increments using a bridge with an accuracy of 1 μV. Conductor lengths were maintained constant at 30 in (762 mm) and the Thompson effect was neglected in the present work.

Each alloy was found to exhibit an almost linear variation of EMF with temperature difference ΔT between the hot and cold junction. In the ΔT range 0–100°C, the deviation from linearity is about -15 μV while the alloys exhibit total thermo-EMF values in the range 300–200 μV at $\Delta T = 100$°C. The thermo-EMF values of the alloys examined were in the same relationship to each other over the entire ΔT range 0–100°C. These relative EMF values are summarized in figure 1 which shows the thermo-EMF values at $\Delta T = 50$°C for a range

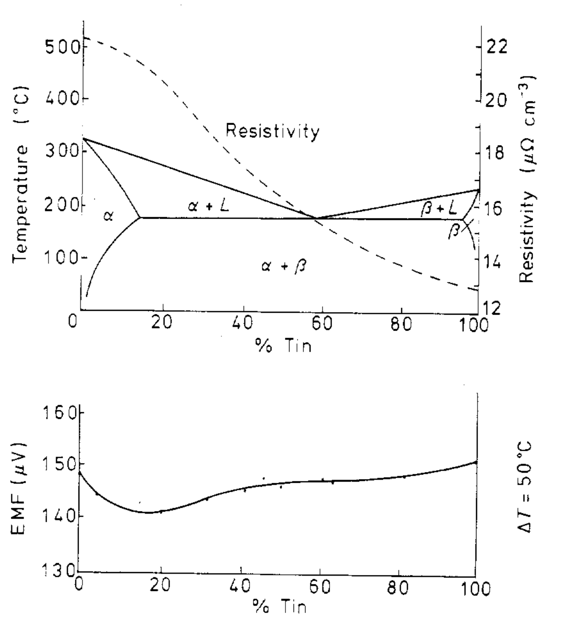

Figure 1 The phase diagram, resistivity and thermo-EMF of the lead–tin system

of alloys, together with the equilibrium phase diagram for the alloy system and resistivity data (Nightingale 1929).

The thermo-EMFs of the lead–tin alloys reach a minimum at about 10% tin which also corresponds to a region of lower slope in the resistivity–composition diagram. It can be suggested that both these effects are related to the amount of primary alpha-phase present and the composition of the alpha-phase. As more alpha-phase will be present in the lower-tin alloys, three-dimensional continuity will cause a decrease in the slope of the resistivity curve and this effect is reflected by a dip in the thermo-EMF–composition relationship. A similar relationship between thermo-EMF and composition has also been noted for magnesium–cadmium alloys (Aleksakhin and Agafonov 1969).

It is to be noted that since cadmium–tin alloys exhibit a thermo-EMF of +4 μV at 25°C ΔT and -45 μV at 100°C ΔT, this alloy is preferred where minimal thermo-EMF generation is specified.

3 Conclusions

This investigation has shown that with copper/tin–lead solder couples used in electronic assembly, possible thermo-EMF generation at the joints is of the order of 145 μV at 50°C ΔT. Such DC voltages should be allowed for in circuit designs for sensitive equipment operating under large temperature gradients.

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