Soldering to Gold Films

THE IMPORTANCE OF LEAD-INDIUM ALLOYS

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Reliable solder joints can be made on gold metallised microcircuits using lead-indium solders providing certain important conditions are understood and carefully controlled. This paper reviews the three fundamental concepts of scavenging, wetting, and ageing, which are relevant when soldering to gold films.

Alloys containing indium have been used for soldering electronic components to thin gold films and wires for at least 14 years. Braun (1, 2) investigated the potential of several multicomponent alloys based upon the lead-tin-indium ternary alloy system. More recently, work on lead-indium binary alloys has been reported by Jackson (3) and Yost, et al (4, 5, 6). In this paper we intend to define, to discuss, and to illustrate three fundamental concepts relevant to soldering to gold films using lead-indium solders.

The lead-indium phase diagram, shown in Figure 1, contains a wealth of useful solder alloys having solidus temperatures which range from 156.6°C (pure indium) to 327.5°C (pure lead). The melting range—liquidus temperature minus solidus temperature—is largest for those alloys lying between 10 and 50 weight per cent indium. There are two peritectic reactions, one at 171.6°C and one at 158.9°C and an intermediate phase, β, which has variable composition and a body centred tetragonal space lattice.

Although considerable work has been addressed to the question of clustering and phase separation in the α field below 20°C (7, 8, 9) the practical significance of this phenomenon has not yet materialised.

The most commonly used alloy is the 50 weight per cent indium composition which has a liquidus temperature of approximately 210°C and a solidus temperature of approximately 185°C. Alloys in the lead rich phase field, α, freeze dendritically by forming lead rich stalks. The formation of these dendrites causes a surface rumpling which gives the solder surface a somewhat frosty rather than a shiny appearance.

A scanning electron photomicrograph showing this rumpling and concomitant dendritic forms is shown in Figure 2. All alloys in the lead-indium system are relatively ductile and even alloys in the β phase field can be coiled and twisted, while an alloy containing

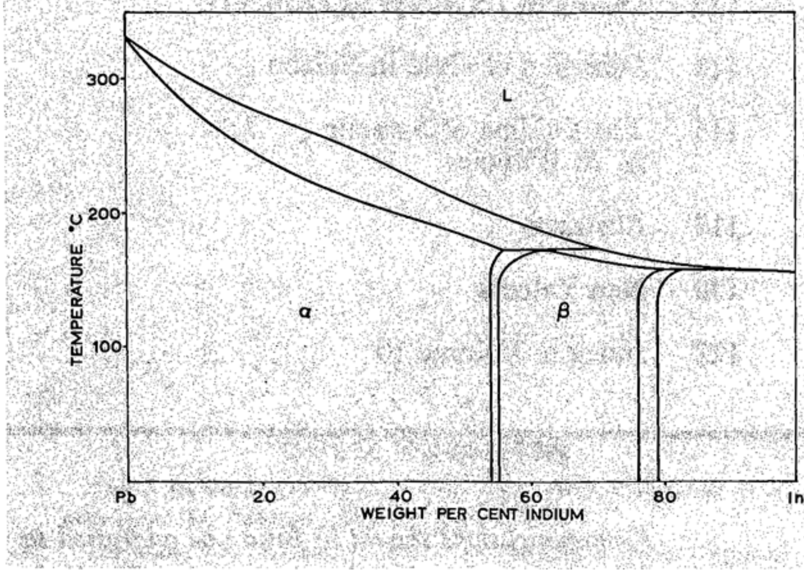
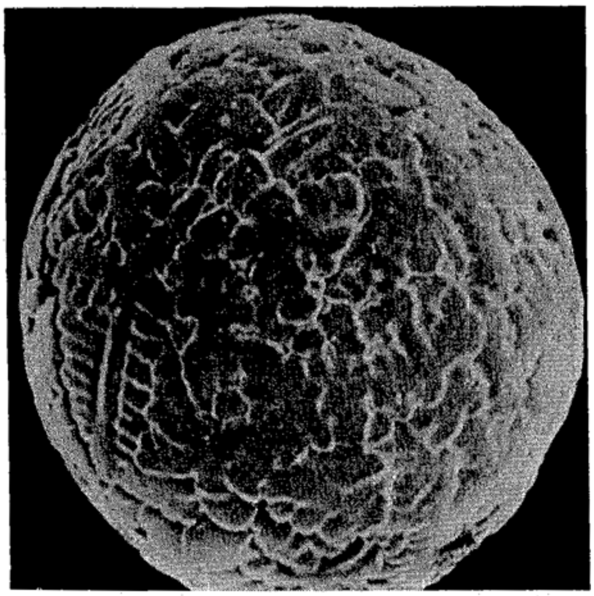


Fig. 1 The lead-indium binary phase diagram, which shows that the melting range is largest for alloys containing between 10 and 50 weight per cent indium

Fig. 2 Scanning electron photomicrograph showing the dendritic form in which the α phase of lead-indium alloys solidify, giving solder joints a frosty appearance ×60



approximately 65 weight per cent indium can be cast and cold-rolled without any intermediate anneals. Many lead-indium alloy solders are commercially available, and in a variety of forms including sheet, strip, rod and fine powder. Discrete components can easily be soldered to plated, vapour deposited and thick film gold as well as bulk gold using a variety of techniques. Pulsed infra-red heating was used to solder the capacitor shown in Figure 3 to a fritless thick film gold surface. Non-activated and mildly activated soldering fluxes diluted with alcohol are quite adequate for most applications. In order to prepare an acceptable solder joint one must consider the substrate wetting capability of the liquid solder in the presence of a suitable flux as well as the substrate metallisation scavenging rate in liquid solder. For long-term reliability of a soldered assembly a thermally aged solder joint must not be brittle or susceptible to fatigue cracking. In the following we shall define the terms scavenging, wetting, and ageing, then discuss and illustrate each one.

Scavenging

We define scavenging as the excessive dissolution of substrate metallisation by liquid solder whereby the soldered parts are rendered useless.

Considerable damage can result when lead-tin solders are used on thin gold film conductor networks. The gold scavenging by 37 weight per cent lead-tin solder is shown in Figure 4 where an attempt was made to solder chip capacitors to fritless gold metallisation using lead-tin solder preforms. The same capacitor and substrate types are shown soldered with 50 weight per cent lead-indium preforms in Figure 5; here no scavenging is apparent. In an attempt to determine why there is such a drastic difference in the gold scavenging behaviour of these two solders, we experimentally constructed the gold-lead-indium ternary diagrams (5). The gold-lead-tin ternary diagram was constructed several years ago by Karnowsky and Rosenzweig (10). From these diagrams we selected vertical sections which represent the solder-gold quasi-binary phase equilibria and these are shown in Figure 6. Notice that at a soldering temperature of 250°C considerably more gold can be dissolved in lead-tin solder than in lead-indium solder. Approximately 1 weight per cent gold must be dissolved in lead-indium before the solid phase $AuIn_2$ can form. Figure 7 shows that this phase coexists with lead in eutectic equilibrium up to 319°C. We have determined that gold film, 6 μm thick, can withstand approximately 15 minutes in molten 50 weight per cent lead-indium solder at

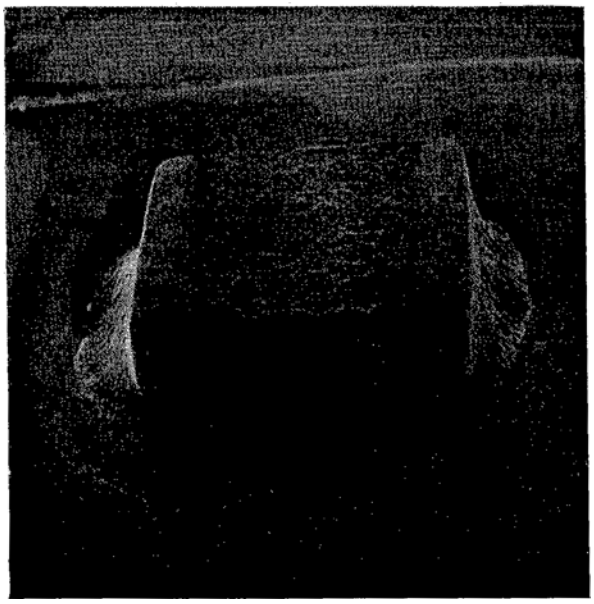


Fig. 3 Chip capacitor with gold terminations soldered to fritless gold thick film metallisation using pulsed infra-red heating ×15

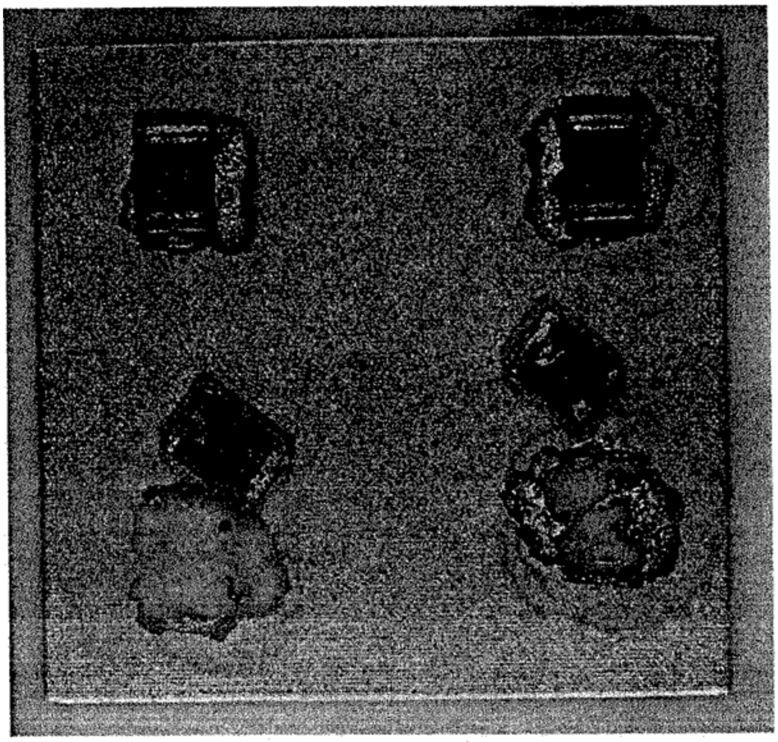


Fig. 4 Gold scavenging by 37 weight per cent lead-tin solder prevents this attempt to solder chip capacitors to fritless gold metallisation

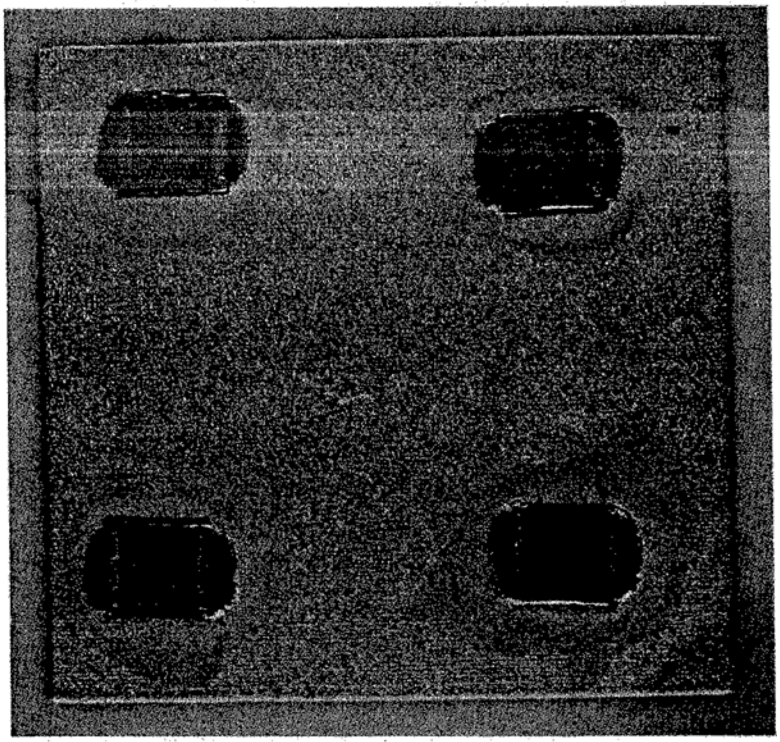


Fig. 5 When 50 weight per cent lead-indium solder is used no scavenging is apparent and the soldering operation is successful

250°C. Consequently, it is our opinion that lead-indium solders do not scavenge gold appreciably.

Wetting

Wetting is defined as that behaviour of liquid solder in contact with substrate metallisation which is characterised by flow and spreading of the liquid until an equilibrium contact angle is established.

Good wetting is generally characterised by contact angles which are less than $\pi/2$ and often approaching zero. Many kinds of wetting tests have been proposed and criticised (11), however we prefer filming the entire wetting event and computer analysing the processed film (6). In our simple wetting experiment,

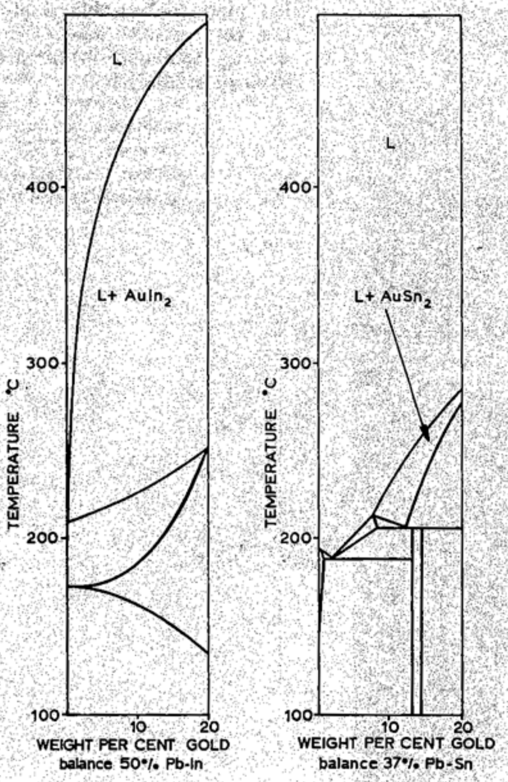


Fig. 6 Vertical sections from the gold-lead-indium and gold-lead-tin ternary phase diagrams showing the large disparity in gold saturation concentrations

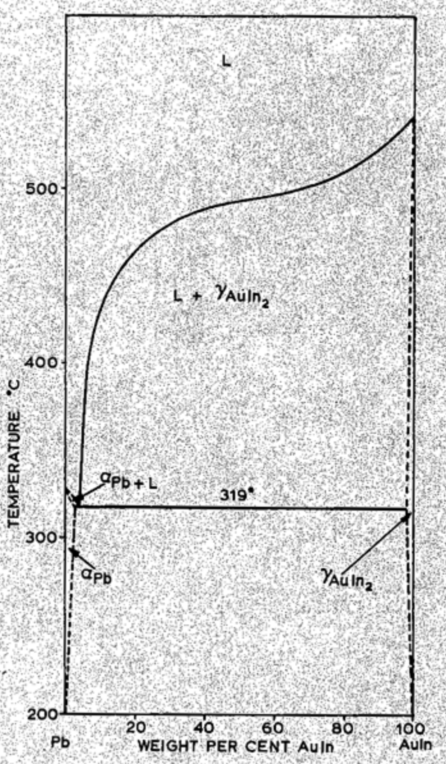


Fig. 7 The quasi-binary lead-AuIn$_2$ system. The AuIn$_2$ phase coexists with lead in eutectic equilibrium up to a temperature of 319°C

shown in Figure 8, the substrate is placed on a hotplate and spray fluxed. When it reaches a steady temperature, as measured by an intrinsically bonded thermocouple, a solder sphere is placed on the substrate. At 40°C higher than the alloy liquidus, spheres 2 mm diameter, and smaller, rapidly and completely melt and begin spreading. Larger spheres melt slowly and incompletely and consequently are not used.

The processed film is then analysed in a film transport and T.V. equipped computer which digitises the film frame by frame and stores the data on magnetic tape; a digitised image being shown as Figure 9. By carefully counting bright and dark raster points in the digitised image the areal fraction of solder can be estimated with great accuracy. If the magnification of the image is known, the actual area of spreading solder can be calculated. The operator can store, on magnetic tape, the data from each frame or from selected frames which can then be plotted or further analysed. Figure 10 shows results from a wetting experiment designed to evaluate fluxes. The area of the spreading solder joint is defined as A, while the radius of the solder sphere is R_o. Using this technique we are able to perform soldering parametric studies very rapidly and without making wetted area measurements by hand.

Ageing

The ageing process is here defined as the irreversible change in solder joint properties due to the thermodynamic interaction of the joint with the environment.

The mechanical properties of a solder joint are largely determined by the way the solder and substrate metallisation react. Shock and fatigue prone joints are often attributed to a brittle intermetallic layer which grows at slightly elevated temperatures. Figure 11 shows Knoop hardness indentations in a bulk gold specimen which was soldered with 50 weight per cent lead-indium and aged at 150°C for 40 hours. Although the Knoop hardness number with a 10g load is higher in the reaction layer (84.6) than in the gold (61.8), it should not be considered a brittle material; in fact, it is quite ductile. The hardness number for soft nickel

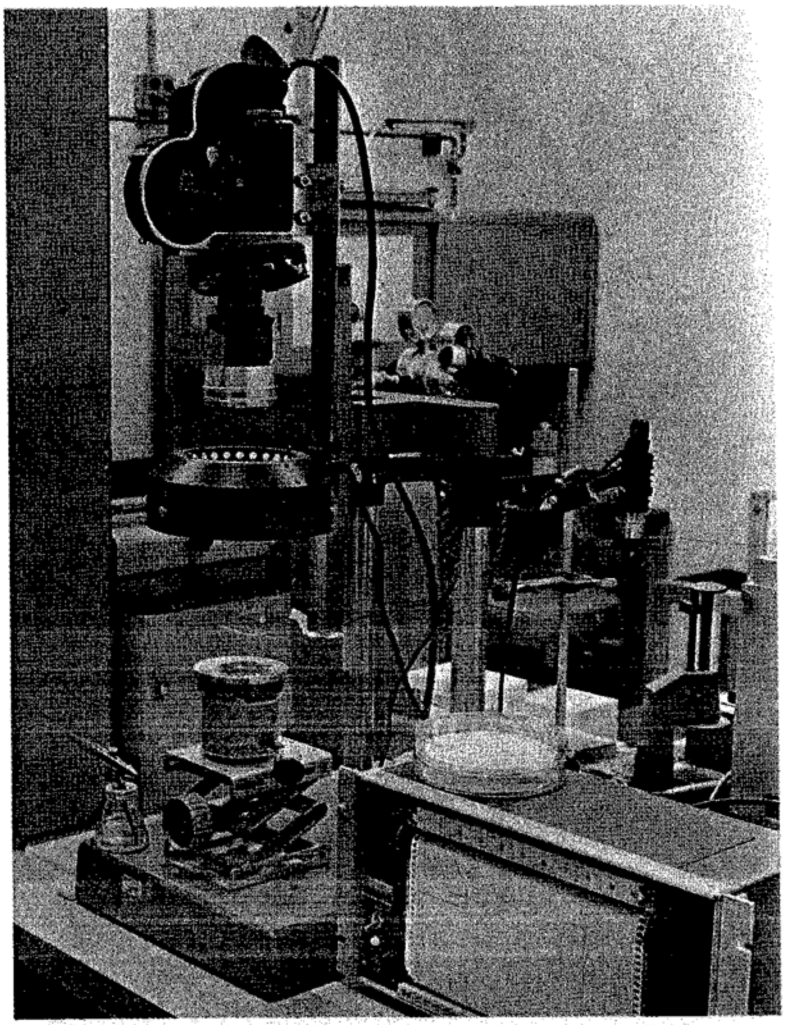


Fig. 8 This equipment, consisting of hot plate, diffuse illumination unit and cine camera, enables the entire wetting operation to be filmed for subsequent analysis

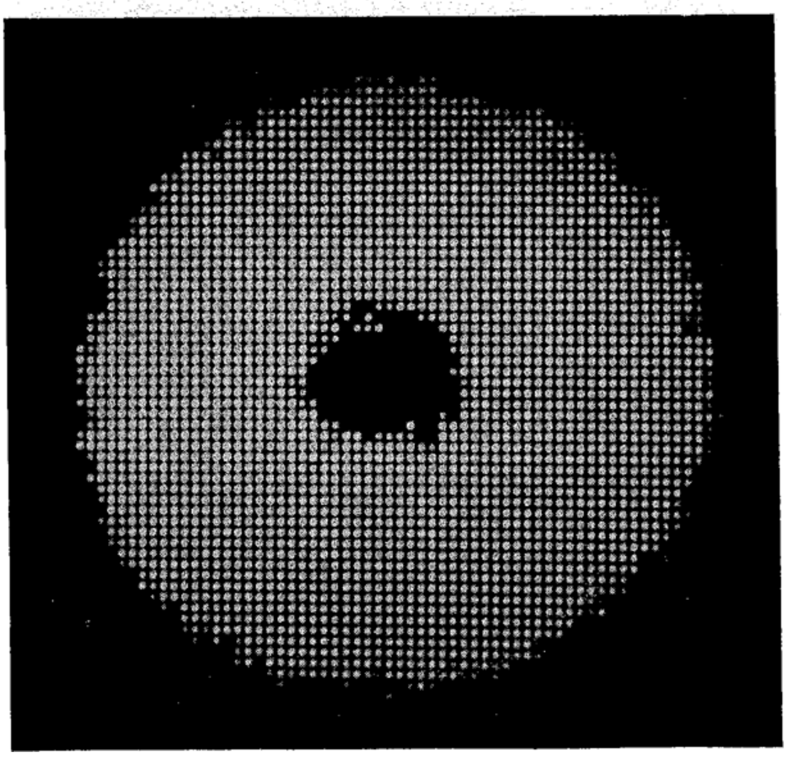


Fig. 9 The processed film which records the wetting operation is analysed by a T.V. equipped computer which digitises the T.V. image of each film frame. One such binary image of a spreading solder droplet is shown here

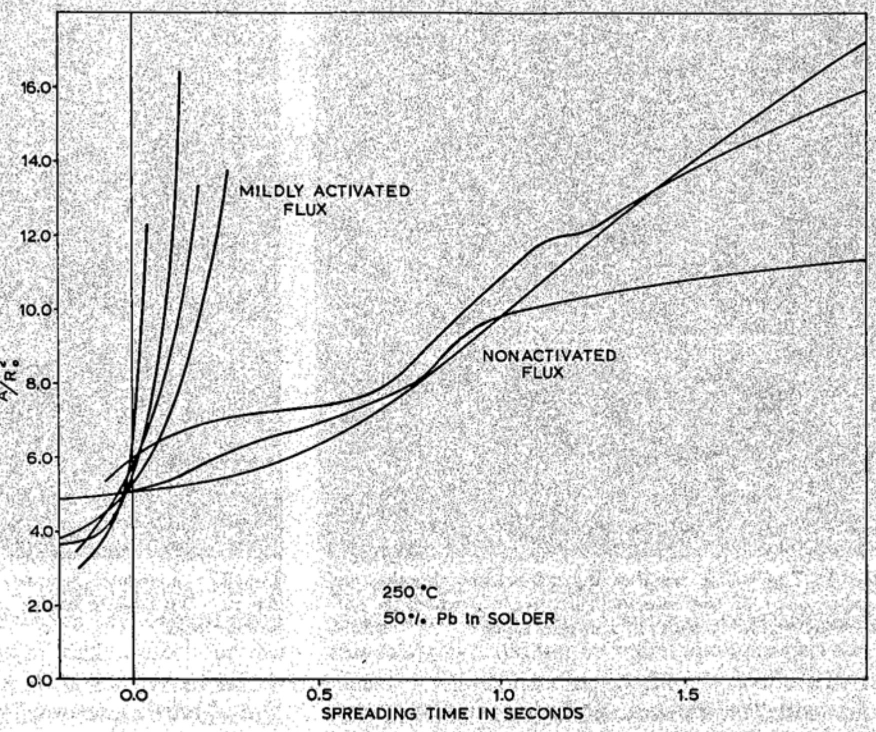


Fig. 10 Experimental results of wetting experiments, carried out using a 50 weight per cent lead-indium solder at 250°C, showing dimensionless wetted area versus spreading time

was found to be 108.3. We have shown (4) that the reason for this ductility is that the intermetallic compound which grows upon ageing is embedded in a lead rich phase. Nodules of this intermetallic, $AuIn_2$, can be seen in the scanning electron microscope fractograph in Figure 12. Normally the reaction layer grows rapidly with an activation energy of 0.61 eV until all the gold is converted to compound. Figure 13 shows a second reaction layer which has been identified as Au_9In_4. Being single phase this layer could impair the mechanical integrity of the solder joint. We have found that it forms when the solder is extremely thin—less than 15 μm—or when the gold film is thicker than about 10 μm. Either of these situations will ultimately lead to indium depletion in the solder at the reaction layer interface. This affords the conditions necessary to form compounds richer in gold than $AuIn_2$.

Conclusions

Three important concepts in the process of soldering to gold films have been presented and discussed. It was shown that lead-indium solders do not scavenge gold as readily as lead-tin solders. Vertical sections from ternary phase diagrams were used to explain this behavioural difference. An efficient means of investigating substrate wetting by liquid

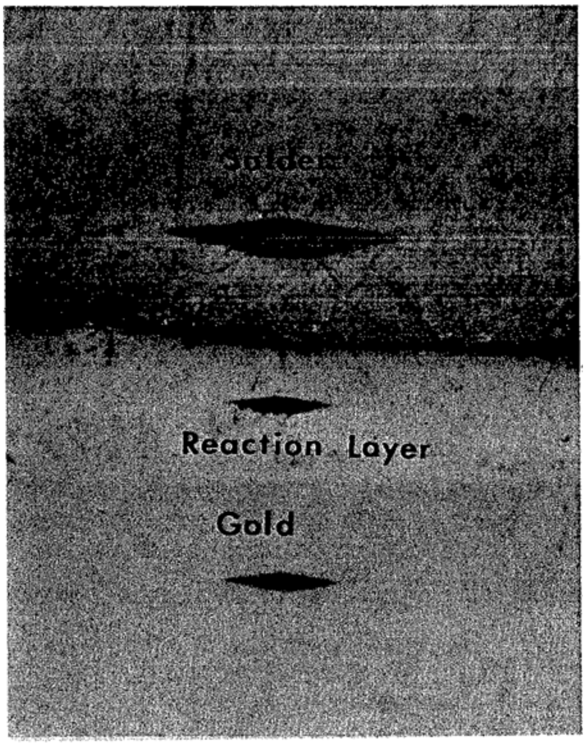


Fig. 11 Knoop hardness indentations made in bulk gold, 50 weight per cent lead-indium solder, and the reaction layer which resulted from ageing at 150°C for 40 hours

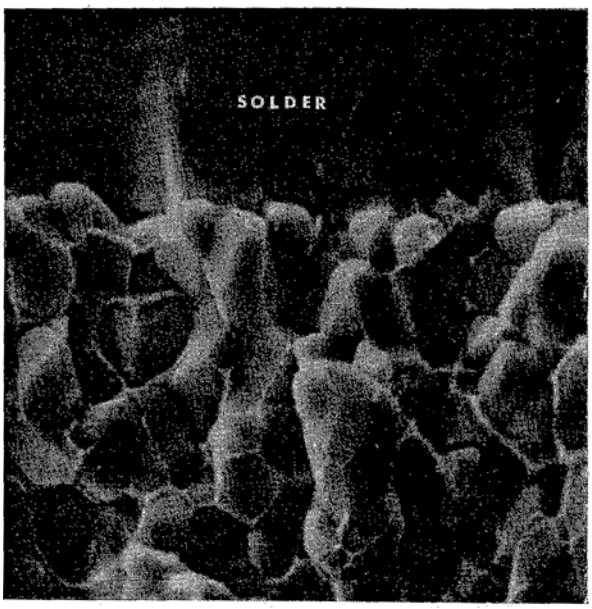


Fig. 12 The solder reaction layer interface showing the nodular form of the intermetallic, $AuIn_2$, which is embedded in lead and results in a ductile layer ×3000

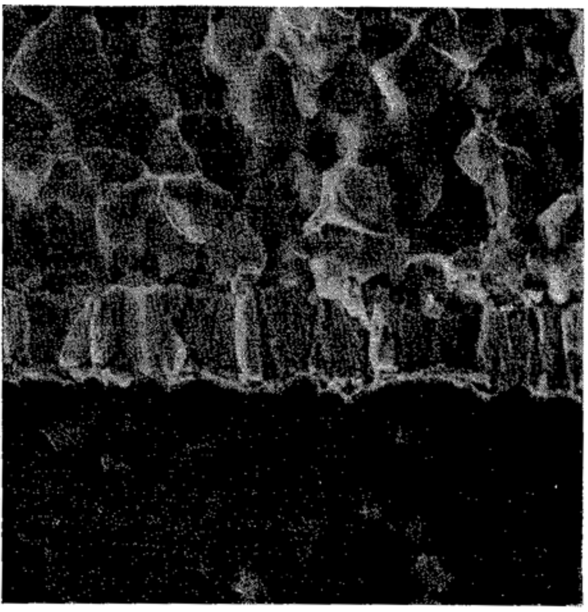


Fig. 13 A second reaction layer consists of columns of Au_9In_4. This could impair the mechanical integrity of the solder joint ×4000

solders was demonstrated. Soldering parameters such as substrate temperature, flux type and solder size can be investigated rapidly and with minimum effort. Ageing of lead-indium solder joints on gold films was discussed in light of the intermetallic reaction layer which grows rapidly. This reaction layer consists of a lead rich α phase which surrounds nodules of $AuIn_2$. This layer was proven to be relatively soft. Conditions necessary for the growth of a single phase layer of Au_9In_4 were stated as thin solder or thick gold, both of which lead to indium depletion which causes compound formation.

Thus, from a fuller understanding of the various factors involved, it can be seen that lead-indium solders cause appreciably less scavenging damage than do lead-tin solders and are therefore satisfactory for use on gold films thicker than 1 µm. In addition, providing the thicknesses of the gold and the lead-indium solder layers are in the correct proportion and the gold layer does not exceed 10 µm, the formation of brittle intermetallic layers can be avoided and satisfactory joints produced.

Acknowledgements

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Radioactive Gold for Investigating the Efficiency of Mixing of Granular Solids

The neutron-heavy radioisotope of gold, $^{198}_{79}Au$, has a half life of 2.7 days and has found application in a number of tracer studies. It has been used for example in investigations on the continuous casting of steel and in following the movement of sea sediments. It has now been reported by A. Rafalski and his colleagues at the Institute for Nuclear Research in Warsaw as an effective tool for investigation of the efficiency of mixing equipment for the blending of granular solids (A. Rafalski, J. Palige, Z. Bazaniak and J. St. Michalik, *Isotopenpraxis*, 1977, **13**, (2), 62–67).

These authors applied the $^{198}_{79}Au$ in the form of solutions of $HAuCl_4$ in hydrochloric acid for the labelling of materials being fed to the mixing installation used for the preparation of the sinter mixtures in a zinc production plant. After application the gold was not susceptible to elution and the method is claimed as being generally applicable to problems of this type.