Soldering technology—
a decade of developments

C. J. Thwaites

Developments in soldering technology during the past ten years have mostly occurred in the electronics industry because of the need to ensure high reliability of soldered joints in such applications. This review covers in detail work concerned with the metallurgy of soft solders including mechanical-property studies, and also basic studies on the physical and chemical nature of the process by which solder wets the basis metals and the means of achieving rapid wetting. Fluxes are essential in the soldering process and more active formulations have been developed to improve wetting or overcome poor solderability of surfaces. Health and safety aspects of these and other materials used in the soldering process are discussed.

New soldering techniques such as vapor-phase soldering using solder creams are included and the question of the routine testing of incoming components for adequate solderability is discussed: the various solderability tests and their application are described. Attention is also given to methods of checking the quality of soldered joints in order to ensure reliability in service and standards relevant to the science of soldering technology are listed.

The state-of-the-art of soldering technology has undergone significant changes since the subject was last reviewed in this journal approximately a decade ago. Since then there has been a considerable increase in the amount of published literature (Table 1). This has derived almost exclusively from the electronics and electrical manufacturing industries or from academic studies associated with processes used in these industries. Much of the work that has been reported is a result of the emphasis on higher reliability in service of manufactured assemblies, better cost effectiveness, and a more realistic approach to fitness for purpose, which have all been achieved in a strongly competitive market. The rapid changes that have been seen, such as the establishment of a micro-electronics industry, the use of the well-publicized silicon-chip technology, together with the massive introduction of electronic devices into the domestic scene and into process control in manufacturing industries, has resulted in a continuing and possibly increased use of soft soldering as the major inter-

connection technique. However, new ways of applying soldering techniques to these latest developments have been devised and this review is largely concerned with these aspects.

The demand for highly reliable assemblies has occurred, in parallel with, and has been partly responsible for, the move towards a reduced use of manual soldering processes and the greater use of mechanized systems such as wave soldering. High reliability in a product, a subject discussed in detail below, when combined with minimum cost is achieved only by careful planning in advance of the product-design requirements and the whole production process so that the optimum materials, processes, and process conditions and controls are clearly defined and are adhered to closely. Such considerations must be reviewed and updated if necessary as newer technologies become available.

The aim of any manufacturing process should be towards a defect-free product from the production line and not to rely on repair and re-instatement work on the assembly. The fallacy in the latter method of operating is most clearly seen in the nominally log-linear relationship between the cost of detecting and curing a fault and the production stage at which it is detected; thus, the elimination of faulty components at the incoming goods inspection stage may be 1000 times less costly than the true cost of locating and repairing a consequent fault in the field (Fig. 1). This clearly ignores the inherent cost due to loss of service of the unit and the imponderable of the inconvenience caused to the consumer.

In reviewing the developments in soldering technology, in the past 10 years, for convenience the subject matter has been divided into sections covering the metallurgy of soldering, materials and processes used, and the properties of soldered joints. Consideration is also given to the important current interest in health and safety, and to national and international standardization work that has been undertaken.

METALLURGY OF SOLDER WETTING

The manufacturing problems associated with the variety of materials used in electronics soldering and the requirement for wetting by the solder in very short times has encouraged many more or less basic studies of the wetting process. Thus, solderability test techniques have become not only an essential production quality control tool, but also a means of gaining a better understanding of factors influencing wetting in the soldering process. The trend in all this work has been to make use of measurements of the force acting on a specimen as it is immersed in and becomes wetted

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was examined by Suezawa using stainless steel and by Collier et al. using tinplate specimens and these workers showed that an inverse relationship existed.

Mathematical treatments of wetting in binary and ternary metallic systems have been published and semiquantitative predictions of wettability based on thermodynamic models were claimed to be possible, but the importance of wetting in practical soldering operations has generally led investigators to concentrate on these aspects, using instruments such as the surface-tension balance. With this technique it was shown by Shipley that in the lead–tin system, the wetting rate was greatest and activation energy least for pure tin and was then not very dependent on temperature. Other results concerned the influence of flux and surface finish. The manner in which the liquid solder meniscus against a flat test plate changes its shape as wetting proceeds, as monitored by a balance was studied by Klein Wassink using high-speed filming techniques and it was demonstrated that an intermittent, step-wise movement of the meniscus occurred especially when using non-activated rosin flux. Maximum climb of the meniscus was seen at the edges rather than at the centre of the test plate, from which it might be assumed that for identical materials and surface conditions, the greater the width of a flat test sheet, the more will the wetting characteristics differ from those of a round wire.

The sessile drop (i.e. area of spread) test is the classical technique used in wetting studies and many thousands of these tests were made by this author in early studies of the solubility of different coatings after extended storage. Raman et al. studied the solubility of stainless steel by area-of-spread tests and concluded that the strength of overlap joints was determined largely by temperature and the efficiency of the flux, and was not related to area-of-spread results. The equilibrium droplet is also used to measure the advancing contact angle of the liquid. Such measurements have been made in the USSR which confirmed that maximum wetting (lowest contact angle) occurred with near-eutectic tin–lead solder on a copper substrate. On nickel, for temperatures of around 500°C, i.e. well above normal soldering temperatures, the smallest contact angle was obtained with much higher lead contents; this was assumed to be caused by the significant solubility of lead in nickel whereas lead is virtually insoluble in copper. In practice, it is found that under normal soldering conditions, nickel is most easily wetted with near-eutectic solders. Howie and Hondonos recently obtained X-ray photographs of sessile drops within a controlled-atmosphere chamber to measure contact angles and carried out parallel experiments on the surface tension of tin, lead, and solder in the presence of flux by means of a maximum bubble pressure technique.

As far as investigations oriented towards practical soldering problems are concerned, the dewetting phenomenon represents the largest single defect that occurs and reasons for dewetting are always being sought. Roberts suggested that fluxes that wetted the liquid solder as well as the substrate could cause dewetting. In other cases

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Table 1 Number of published papers revealed by computer search using keywords SOLDER and SOLDERING

<table>
<thead>
<tr>
<th>Inclusive period</th>
<th>Number</th>
<th>Per cent increase in 5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966–1970</td>
<td>285</td>
<td>...</td>
</tr>
<tr>
<td>1971–1975</td>
<td>406</td>
<td>42</td>
</tr>
<tr>
<td>1976–1980</td>
<td>621</td>
<td>53</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>1312</strong></td>
<td><strong>218%</strong></td>
</tr>
</tbody>
</table>

by liquid solder, i.e. using a surface-tension (wetting) balance. For example, Prof. Okamato’s group at Osaka University have published work on the problem of non-wetting and have demonstrated that if a test specimen is immersed to more than 2.5 mm depth, hydrostatic pressures will remove a non-activated flux from the surfaces below this depth so that oxides are not dissolved and non-wetting is seen on withdrawal of the sample. This means that in the standardized solderability test where the immersion depth is 2–2.5 mm, good wetting might be indicated for components which when soldered under production conditions to a greater immersion depth would exhibit wetting defects. Other studies at Osaka University have been concerned with fluxing reactions (see below) and seeking an explanation of why the area of spread of solder on a given surface is greatest for near-eutectic tin–lead solder whereas the penetration of solder into a vertical capillary space formed by the same surfaces is greatest for pure tin in agreement with Latin’s work. Takahashi and Nagasawa showed that wetting rate, as determined by a surface-tension balance, increased with tin content but this could not be explained solely on the basis of the balance of interfacial tensions expressed by Young’s equation. They also stated that wetting rate was sometimes related to equilibrium spreading of solder. The effect on wetting rate of the surface roughness of the test samples...
electron microprobe analysis indicated the presence of sulphur as well as tin concentrations at the substrate surface from which solder had dewetted, suggesting that sulphur might well be an undesirable element in the solder and perhaps in the substrate metal as well. It is known that sulphur in lead-rich solders used in tinplate can soldering can cause dewetting of the solder coating on the roll of the can soldering machine. Another associated fact, confirmed at the author’s laboratory, is that a badly dewetted solder coating usually exhibits a lead-rich layer adjacent to the intermetallic compound layer formed on copper. The presence of zinc in solder can also affect growth of the copper–tin intermetallic compound layer (Fig. 2) and so produce defective wetting by the solder. Inclusions in the substrate surface which do not wet were shown by Klein Wassink to be one reason for dewetting and he found that only a small proportion of the surface need have non-wetting inclusions to induce dewetting of the solder film. These effects had been reported earlier.

The practical implications of surface reactions occurring during a soldering operation have been studied, such as the rate of dissolution of copper as fine wires, in different liquid solders from which a mathematical model was established for the dissolution and copper–tin diffusion rates; Allen measured dissolution rates by the time required to break fine wires under load and concluded that a solder already saturated with copper was preferred. Activation energies for diffusion between 200 and 450°C in the iron–tin and copper–tin systems were calculated from work based on microprobe analysis. In the nickel–tin system Kang and Ramachandran stated that the diffusion rate of nickel in tin was the controlling factor in the growth kinetics of Ni₅Sn₄ and Ni₅Sn₃, the former being the predominant compound; Ni₅Sn was not observed. Schmitt-Thomas and co-workers used scanning electron microscopy to study the interrelation between intermetallic compound layer characteristics in soldered joints and fracture behaviour and monitored crack formation and propagation by acoustic-emission analysis. This group also studied compound growth during the industrial wave-soldering process for printed circuit boards especially in plated-through holes.

The soldering of gold-coated substrates has always presented problems because of the extremely rapid reaction of gold with tin in the solder and its high dissolution rate which can result in low-strength joints, owing to separation of the Au₅Sn₄ layer from retracted gold. Kehrer and Wenzel propose that this weakness is mostly caused by lead enrichment at the intermetallic compound/solder interface. Many studies have sought alternative solder alloys and in particular the indium–lead system because the formation of Au–In compound layers is slow and apparently does not cause embrittlement problems as with the Au–Sn compounds that are formed. The influence of the surface roughness of the non-metallic substrate on the rate of solution of thin gold films fired on as a paste containing metal powder and glass powders was examined by Rickabaugh. The practical implication being that a sufficient heat treatment is essential to allow the glass to diffuse into the substrate and leave a gold-rich surface which can be wetted by solder. The nature of the intermetallic compound layers in joints on actual production reflow-soldered components on printed circuit boards was examined by scanning Auger spectroscopy and it was found that poor wetting corresponded to a tin content of the solder at the interface well below the nominal eutectic level. It was also observed that in the nickel–iron–cobalt alloys used for glass–metal seals, a low nickel content corresponded to poor wetting properties, but this fact is difficult to explain. Interfacial reactions during the soldering of commercial-quality aluminium using...
four different lead-rich alloys were studied with
electron microprobe analysis by Schwanke et al.\textsuperscript{34}

During the wetting of a substrate by a liquid
filler metal, diffusion occurs both normal to the
interface (to form, usually, intermetallic compound
layers) and, to a greater distance, in the substrate
surface itself as shown by Lea\textsuperscript{35} for indium–tin.
The indium travelled further ahead of the advancing
liquid/solid interface than did tin.

The above has been concerned with the liquid–
solid reactions occurring during soldering but it
must also be borne in mind that tin alloys at tem-
peratures between ambient and the common elec-
tronic assembly or heat-exchanger operating tem-
peratures (≈100°C) will also react by solid-state
diffusion with most substrate metals. Thus, a
soldered joint will initially contain thin (about
1 μm) layers of intermetallic compound at the
solder/substrate interface but with time at ele-
vated temperatures this layer will grow and may
eventually affect joint integrity.\textsuperscript{36} However, recent
work at the author’s establishment showed signifi-
cant effects on joint strength only at high rates of
deformation including slow-cycle fatigue, pre-
sumably because the brittleness of the compound
was more easily accommodated at low strain
rates (Table 2). The second effect of solid-state
diffusion to be considered is the influence on the
solderability of coatings of a period of storage
before being soldered, as may happen under in-
dustrial conditions. It has been shown\textsuperscript{37,38} that
at room temperature, surprisingly, pure tin and a
90Pb–10Sn alloy coating show the highest com-
 pound-layer growth rates whereas at high tempera-
tures a 60Sn–40Pb coating shows the lowest
growth rate. By studying the effect of a pure lead
interlayer, it has been shown that tin and copper
form Cu₅Sn₅ faster when the tin first diffuses
through a lead-rich layer than by direct reaction.\textsuperscript{39}
This work has enabled activation energies to be
calculated from Arrhenius plots and, of com-
mmercial importance, the rate of loss of coating
thickness caused by conversion to intermetallic
compound can now be predicted for any tempera-
ture up to near the melting point of the coating for
a variety of substrate metals. It was also observed
that only an iron undercoat layer on copper is a
true effective barrier against significant solid-
state diffusion of tin at temperatures such as
170°C.\textsuperscript{39} These investigations also included ex-
amination of the nature of the intermetallic com-
 pounds formed and it is of interest that when a tin
coating reacts with brass, only Cu₅Sn₅ is formed
which, however, contains some zinc in solid solu-
tion, whereas on copper Cu₅Sn may be formed as
well as Cu₅Sn₅ at the compound/substrate inter-
face a layer of β-brass was observed. Kay\textsuperscript{40} has
reported on the initial studies of the effect of com-
pound layer thickness and of residual non-reacted
tin or tin–lead alloy coating on solderability which
is the important practical aspect on which data is
required.

The activation–energy values derived by Kay
and MacKay\textsuperscript{37} for the Cu–Sn(–Pb) system were
lower by a factor of about three than those given
in a more recent paper\textsuperscript{41} and this can be explained
by the hypothesis that in a system where several
intermetallic compound layers form, layer-by-layer
behaviour changes with temperature so that it is
not acceptable to extrapolate from elevated tem-
peratures to room temperature as was done in the
latter paper.

Brass has desirable properties and low cost
for the manufacture of many piece parts and is
often tin coated by plating or a hot-dipping process
to provide solderability and Stuer et al.\textsuperscript{42} have
studied the growth rate of the compound layer at
80–150°C for times up to 1000 h. The results are
broadly in agreement with the results mentioned
above.\textsuperscript{37,38} They also found that the intermetallic
compound layer on copper–nickel–tin and copper–
nickel–zinc (nickel silver) substrates formed by
reaction with liquid solder and then heat treated
was basically Cu₅Sn₅ containing, respectively, 3
and 10% Ni in solution.

Panusius and Hall\textsuperscript{43} examined the grain-
boundary diffusion of thin gold coatings on copper
at 50–300°C for periods up to 10 000 h by Auger
spectroscopy. They demonstrated that solder-
ability deteriorated because copper diffused to the
outer surface to form a non-wetting layer of Cu₂O.
Diffusion in the duplex-coating system gold over
tin–nickel alloy on a copper substrate was studied
by other investigators\textsuperscript{44} following the general
trend in the electronics industry to attempt to
eliminate or reduce gold usage.

The above demonstrates that although there
has been, and always will be, a desire to study the
fundamentals of the wetting process in soldering,
much of the experimental work is orientated
that this metallurgical reactions occurring at
the solder/substrate interface because these can
have a profound effect on the integrity in service
of the finished soldered assembly.

### SOLDERING ALLOYS

According to certain definitions, soft solders are
filler metals for capillary joining with a melting
point below 450°C, while filler metals for use

<table>
<thead>
<tr>
<th>Time at 170°C, days</th>
<th>Compound-layer thickness, μm</th>
<th>In shear at, 0.05 mm min⁻¹ 50 mm min⁻¹</th>
<th>Creep (1000 h life)</th>
<th>Fatigue (2000 cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>20</td>
<td>48</td>
<td>3.5</td>
</tr>
<tr>
<td>200</td>
<td>32</td>
<td>21.5</td>
<td>34</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Table 3 Some suggested limits for elemental contamination of 60Sn–40Pb solder bath

<table>
<thead>
<tr>
<th>Element</th>
<th>Maximum, wt-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>0.0005</td>
</tr>
<tr>
<td>Antimony</td>
<td>0.2 or 0.5*</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.05</td>
</tr>
<tr>
<td>Bismuth</td>
<td>0.1</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.25</td>
</tr>
<tr>
<td>Gold</td>
<td>0.11</td>
</tr>
<tr>
<td>Iron</td>
<td>0.02</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.05</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.0005</td>
</tr>
<tr>
<td>Silver</td>
<td>2.0</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.0015</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.003</td>
</tr>
</tbody>
</table>

*BS 219 limits.
10.01% max. preferred for soldering brass.
2 Levels approaching 1% are technically acceptable.
30.00001% for can-body soldering with lead-rich solder.

above this temperature are brazing alloys. However, the most widely used solders are based on the lead–tin binary system while other alloys for special purposes are tin- or lead-rich. This review, therefore, will examine in this section only those solder alloys with liquidus temperatures up to about 330°C, which is a limit being proposed by a new international standardization working party.

First, considering literature connected with the commercial application of the existing solder alloys, the US specifications MIL-454 and WS-6536 give suggested maxima for impurity elements in solder baths, based probably on practical experience. Elliott has reviewed the subject of bath contamination.

Raman made laboratory studies of the effect of metallic additions on the area of spread of solder. Ackroyd et al. showed in laboratory solderability tests the influence of different impurity elements on wetting by a high-purity 60Sn–40Pb solder and derived some suggested limits for certain single elements (Table 3). This work showed that a major effect of some elements was in inducing rapid oxide formation, which is a commercial problem in wave-soldering machines. As a result, an experimental technique was evolved for inducing oxidation by stirring a solder bath and the influence, initially of temperature, time, and tin content was reported by Stoneman et al., while later work concentrated on the relative effects of single-element additions on oxidation rate.

An effect observed which has yet to be explained is a point of inflexion in all of the weight gain v. temperature curves that were obtained, whatever the addition element, though this region corresponded with a change in the dross formed on the surface of the molten solder. Phosphorus additions were also beneficial in reducing oxidation rate (Fig. 3). Tumlinson and Martin also studied oxidation of a 50Sn–50Pb solder but at temperatures well above those used in soldering, namely, 550–650°C and it cannot be assumed that the results can be extrapolated down to 250–300°C to make them of practical usefulness. Okamoto et al. used Auger and electron spectroscopy to study the oxidation of solder and reaction with water vapour and nitrogen dioxide.

Antimony may be present in tin–lead solders usually as a result of recycling of antimony-bearing scrap in the production of secondary solder, or it may be deliberately added. The deliberate use of antimony additions to the extent of several per cent, which effects a cost saving by reducing the tin content from 50 to 50%, has been well documented as in Ref. 51; this paper indicates no increase in oxidation due to the presence of antimony, in contrast to the results of Stoneman et al. Coleman studied the validity of the opinion of industry that the use of antimony-bearing solders on brass resulted in brittle soldered joints and did not observe the reputed formation of the Sn–Zn intermetallic compound claimed to cause the brittleness. Experiments in the author’s establishment have confirmed these

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findings (Fig. 4) but it appears that the fracture propagation mechanism is changed by the presence of antimony. Wetting-balance tests on various substrates by Edwards demonstrated the superiority of pure 60Sn–40Pb solder though some of the experimental results were ambiguous and unexplained. Ackroyd et al.8 also showed in earlier work the detrimental influence of antimony additions on wetting. Other experiments showed that when soldering gold-coated surfaces, 3%Sb in a 60Sn–40Pb alloy suppressed the formation of AuSn2 which had been found to be responsible for the dewetting and detachment of the AuSn2 layer from the unreacted gold layer.69

Additions of copper to tin–lead alloys are made commercially in order to saturate the liquid metal at the normal service temperature and so reduce dissolution and erosion of unclad copper soldering-iron bits or fine wires and studies on the relative rate of attack of this and other solder alloys on copper have been described.23,51,66 An interesting development was the possible use of ruthenium-clad soldering-iron bits which wetted but were claimed not to be attacked or eroded.57

Referring again to studies of new solders for making reliable joints on gold surfaces, Duckett and Ackroyd examined a number of alloys, assessing them by peel-strength tests on overlap joints and found that the presence of cadmium suppressed the formation of the brittle compound AuSn4, but the effect was not reproducible. All of the most recent work has shown that indium-containing solders may be preferred to reduce gold leaching and basic studies on such systems have been carried out.51,62

Alloys for soldering copper water-piping systems were discussed by Sosnin,63 who stated that the higher melting point and hence higher strength Sn–5Sb alloy was likely to give more voids in the joints because of inferior capillary penetration compared with tin–lead solders. The corrosion aspects with respect to the leaching out of lead have been studied.44,45 Gram65 indicated that the trend in Scandinavia was to use lead-free solders such as Sn–5Ag; the added cost being small in relation to the total installation cost.67

Solder alloys for use on aluminium and its alloys are frequently based on the tin–zinc system or cadmium–tin, but an alternative Pb–10Sn–2Ag solder in combination with a non-corrosive flux of unspecified composition has been described by Allen.71 A process for the continuous coating of aluminium strip to make it solderable consists of immersion in a tin, lead, zinc, or cadmium bath containing 0.005–0.05% Ga, with accompanying processes to rupture mechanically the aluminium oxide surface skin on the strip; it is claimed the gallium diffuses along the oxide/substrate interface thus lifting off the oxide and allowing wetting by the molten coating metal to occur.72

More difficult to wet by solders are silicon, germanium, ceramics, and glass, and in a patent it is suggested that a tin–cadmium alloy also containing zinc, antimony, bismuth, plus a rare-earth metal will wet such materials with the assistance of ultrasonic cavitation;73 the alloys mentioned have liquidus temperatures between 70 and 180°C. A similar approach using the potential reactivity to oxygen of rare-earth elements was applied to tin–lead solders for use on silica, etc.74

Lead-rich alloys have inferior wetting properties to those of higher tin content but are useful in the soldering of metallized microcircuits. Mitsugi et al.75 described the cladding of such lead-rich solders with a thin surface layer of tin which apparently improved the solderability characteristics significantly without changing the overall composition of the solder preform. However, the results reported were for a solder-spread test at a temperature of 400°C in a hydrogen atmosphere so that strictly they are only related to the soldering of semiconductor devices.

Electronic assemblies contain soldered joints which may carry microamperes at only microvolt levels and concern has been expressed over possible Peltier effects at the multiple-metal interfaces. Pascoe has reported on the thermal emf values generated by different solders and sometimes a 70Cu–30Sn alloy is used to eliminate voltage generation at the joints.77

Filler metals that can be used at temperatures lower than those suitable for tin–lead solders or
even at room temperature have always been of interest and ten Duis\textsuperscript{78} has compared the wetting properties of some Sn–Pb–Bi and Sn–Pb–Cd alloys with conventional solder compositions, using different substrates and both resin-based and aqueous fluxes. It was shown that for a given short wetting time, the lower melting alloys could be used at up to 50 K lower than the temperature of tin–lead alloys depending on the specific flux and substrate. Another alloy containing 21\%In with a melting point of 58°C was proposed by Ward\textsuperscript{79} for precoating surfaces in place of tin or tin–lead alloy and this gave good solderability. Powder mixtures of, for example, copper and tin have been mixed with gallium at room temperature to provide wetting of the surfaces to be soldered and a strong metallurgical bond subsequently developed by a heat treatment such as 1 h at 150°C.\textsuperscript{80}

Lead-rich solders are used for the filling of weld areas on automobile bodies and require to be of a 'putty' consistency. The alloy is applied at a temperature between the liquidus and solidus and studies have been concerned with the spreadability of the alloy\textsuperscript{81} and on the microstructural changes that occur during the process.\textsuperscript{82}

Referring briefly to the properties (other than mechanical) of solder alloys, Warwick and Hampshire\textsuperscript{83} have summarized the literature on atmospheric corrosion of tin–lead alloys. Corrosion of solders within a joint is not a commonplace problem but Warwick\textsuperscript{84} has reported laboratory simulation of the internal corrosion of tinplate cans containing a soldered side-seam in which increasing the tin content of the solder from the conventional 2\% (balance lead) to 20–30\%, virtually eliminated lead dissolution into the simulated food. A new alloy to prevent sulphur staining of the soldered side-seam of tinplate cans has also been proposed\textsuperscript{85} which contains small amounts of indium and bismuth. The corrosion behaviour of joints in automotive heat exchangers subjected to different coolant fluids was investigated by Falke \textit{et al.},\textsuperscript{86} who found that fluid type and temperature had a larger effect than did solder composition.

An interesting study was made by Durham\textsuperscript{87} on the quantification of the solidification characteristics of solders and he demonstrated the effect of wetting at the solder/substrate interface on thermal transfer. Heat extraction by the substrate was much greater with tin-rich alloys than with lead-rich solders. The viscosity of tin–silver alloys was the subject of a study by Nakayama.\textsuperscript{88} Much of the other fundamental work has concentrated particularly on the superplastic behaviour of eutectic tin–lead alloys\textsuperscript{89–94} because this material represents an ideal case for the study of the microstructural changes that accompany deformation.\textsuperscript{95} Ternary alloys have also been investigated.\textsuperscript{96} However, it is clear that the above studies bear little relation to the practice of soldering technology.

The initial results of a comprehensive programme of comparative data on different solder alloys were published by Stone \textit{et al.},\textsuperscript{97} as part of a study of the strength of solders and joints made with the same solder alloys; the latter aspect is discussed below.

Although there have been many studies of the tensile properties of solder alloys, and some mention of this work has been made in the preceding section, in practice it is the endurance of the soldered joint under load that is important; it has been suggested that the order of merit for different alloys based on mechanical-strength considerations can be different when joints made with the same alloys are tested.\textsuperscript{97}

Soldered joints of different geometries may be used for mechanical-property studies and the relative merits of butt, overlap strips, and ring-and-plug testpieces have been discussed,\textsuperscript{98} the conclusion being that the last (which is covered by ISO 2688) is a preferred design for investigational work. A novel technique for the insertion of three non-wetting wires to ensure a uniform joint clearance was described. The marked influence of testing rate on tensile strength of both bulk solders and joints was also shown in this work (Fig. 5) and by Chen \textit{et al.}.\textsuperscript{99} Other proposals for soldered joint testpieces have been made.\textsuperscript{100} Shawki and El Sabbagh also studied the effects of joint design and testpiece size on the shear strength of soldered joints.\textsuperscript{101}

In an increasing number of industrial applications, stress and/or temperature conditions have increased so that the resistance of joints to creep and/or fatigue at elevated temperatures or under cyclic temperature variations has become a common subject for investigation. Nesse \textit{et al.}\textsuperscript{102} studied the creep resistance at room temperature of joints between copper or steel members made with 95Sn–5Ag alloy and Nesse\textsuperscript{103} went on to compare the creep resistance of different alloys including cadmium–zinc–silver alloys, which have melting points in the range 280–375°C. Foehr and Prager\textsuperscript{104} demonstrated in practical tests that in the soldered joints in copper tube fire sprinkler systems the resistance to creep under pressure at elevated temperatures was much greater for a 96Sn–4Sb alloy than the usual tin–lead soldered joints but that better workmanship was required because of the higher melting point of the former alloy. This confirmed the ideas of Sosnin\textsuperscript{63} mentioned above.

![Graph](attachment://Graph.png)

\textbf{c} bulk solder tensile strength; \textbf{b} overlap joint made at 240°C; \textbf{c} ring-and-plug joint made at 280°C

\textsuperscript{5} Marked effect of crosshead speed (straining rate) on tensile strength of Cu soldered with 60Sn–40Pb (Ref. 98)

\begin{center}
\textbf{International Metals Reviews, 1984, Vol. 29, No. 2}
\end{center}
A comparison of shear strength at various temperatures of joints made with 60Sn-40Pb alloy as a control and various other low melting point alloys containing indium or bismuth, was made by Wild. Stress-relaxation and stress-to-rupture tests were also made on overlap joints and showed the Bi-Sn eutectic alloy to have greater shear and creep strength than the control alloy at 60 and 80°C, but not at room temperature or below 0°C. Creep studies on joints to circuit boards and on test pieces were also described by Le Penven and Gabard.

Automotive radiators and heat exchangers have presented increasingly arduous stress and temperature conditions for the soldered joints, which are an essential part of the traditional copper-brass tubing, and a comprehensive study led to the recommendation that lead-rich alloys with small and very specific amounts of tin and silver provided the best joint strength as measured by the fracture initiation and propagation loads in a peel test. Studies on the wetting properties of a Pb-5Sn alloy containing up to 1.5%Ag and/or Sn were made by other investigators using a surface-tension balance. They showed that all additions progressively increased wetting rate on copper. Working in the same technological area, Schwanke et al. proposed a Zn-5Al alloy for higher joint strength in heat exchangers made of copper alloys or mild steel and claimed good wetting, but the process required that the substrate should first be nickel coated by a suitable means. Corrosion studies in automobile coolant liquids were also reported for these new alloys.

The area of greatest interest has been that of thermally induced fatigue of soldered joints in electronic assemblies resulting from differences in thermal-expansion properties of the materials employed. The work of Wild mentioned above developed into mechanical- and thermal-fatigue studies using changes in electrical resistance to monitor the onset of cracking. Thermal-stress analysis has been carried out by Kobayashi, Dunn, and examined the resistance of joints made with near-eutectic tin-lead alloys to temperature cycling between -60 and +70°C, this being the range applicable to spacecraft applications. The better stress-relaxation properties of the binary tin-lead alloy was claimed to give better thermal-fatigue resistance than the less ductile alloys containing additions of silver, copper, or antimony. Bangs and Beal also studied the thermal-cycling fatigue resistance of different solders over a wider temperature range of -65 to +150°C. The practical fatigue testing of joints on printed circuit boards was carried out also by Wild, Blanke, and for microcircuits by Kinser et al. Olsen and Berg claimed the development of a new solder for die bonding, intermediate in strength (about 140 MNO2 at room temperature) between the 'hard' gold-tin or gold-silicon alloy and the conventional tin- or lead-based solders, but the actual composition was not disclosed. However, a lead-rich alloy of improved fatigue resistance was described by other workers. This alloy contained considerable quantities of cadmium and zinc which on other evidence would be likely to give oxidation or wetting problems and possibly a health hazard in use.

The bond strength of wires of different composition soldered in plated-through holes which had various thicknesses of gold plating was shown by Kehrler and Wenzel to be related to the wire-hole diameter ratio (i.e., joint gap) and gold-coating thickness, while other investigators, e.g., Mika, have examined the peel strength of flat pack leads of integrated circuits soldered on to the surface of a printed circuit board by different processes and have concluded that the use of electrical resistance heating gave the most reliable bonding.

The mechanism of fatigue of soldered joints caused by thermally induced damage was discussed in relation to the intermetallic compound layers and it was concluded that a lead-rich alloy with small amounts of tin and cerium was most resistant to thermal damage. Other investigators have considered the problem of joint failure on printed circuit assemblies and have discussed the influence of component mounting techniques on the propensity for fatigue cracking of the solder under fluctuating temperature conditions.

In the application of soldered joints in areas other than electronics, Weyers and Warner discussed the creep resistance of tinplate can side-seams soldered with the conventional 98Pb-2Sn alloy and 100%Sn, the latter being advocated for certain applications where lead must be absent. MacFarlane and Ress studied the interrelation of coating thickness, passivation treatment, and surface roughness of tinplate with wetting properties and joint strength and showed that the material with the greater thickness of coating together with the smoothest surface gave the highest joint strength and that low strength values were usually associated with poor wetting and bad penetration of the joint space.

A number of other papers have been published on the mechanical properties of soldered joints but the above can be seen to demonstrate that the bulk of the work has been related to practical problems, such as creep and fatigue failures, arising from the increasingly arduous service conditions seen especially in certain electronics applications and also in heat exchangers.

**FLUXES AND FLUXING**

 Fluxes for soft soldering have the basic purpose of helping to provide surfaces on the basis metals and on the liquid solder which are free of films such as oxide which would interfere with the wetting process. They are, therefore, chemicals which react with metal oxides but can act also as a blanket to exclude oxygen from the surrounding atmosphere. Fluxes are largely proprietary in composition and each is designed to have certain specific characteristics. For non-critical applications and where flux residues can readily be removed, quite strong acid or inorganic halide fluxes may be employed, but for many years, only relatively low-activity fluxes based on natural wood rosin (colophony) have been allowed for soldering electrical and electronic assemblies.
In recent years, the cost of reworking soldered joints of unacceptable quality produced during the machine soldering of electronic assemblies has led to the introduction of certain aqueous acid fluxes to help overcome the intermittent problems of poor solderability of component parts that lead to defective joints. Whereas this represents an important development and many of the papers referred to below are related to this aspect, nevertheless the bulk of soldered joints in electronics applications are still made with the aid of rosin-based fluxes because of natural resistance by industry to change and the additional requirements for flux removal and residue monitoring systems when using aqueous fluxes. The pros and cons of fluxes based on rosin in organic solvents and of water-based inorganic or organic acid fluxes for electronics assembly work have been reviewed in many papers. To date the more vigorous aqueous organic fluxes have not been approved for military or similar installations where long-term reliability is vital.

Rosin-basis fluxes

Complex organic fluxes such as those based on natural rosin are difficult to analyse both for their constituents (which may include activators such as amine halides or organic acids/halides) and for their ability to act as a flux. Rubin and Lovering have described the use of TGA-DTA to characterize fluxes and their activators and found that several activators added to rosin decompose at a similar temperature to the rosin basis itself. Carboxylic acids as well as a new non-rosin type flux were also examined. Kosarec and Rux also used DTA as a means of comparing fluxes. The non-rosin basis of Rubin consisted of a formulation such as pentaerythritol tetrabenoate, usually with an added activator, which is stated to produce less fume and can be combined with solder powder to form a paste or used as an etch-resistant film in printed circuit board manufacture. Kurjat discusses means of improving the established rosin-type fluxes used in fluxcored solder wire and disclosed results with five different amines. In more recent years, the analysis of flux behaviour has mostly been studied using the surface-tension balance to obtain a quantitative assessment, as described by Denison. Audette and MacKay also compared the activity of fluxes complying with certain USA specifications by this method, but using standard sulphide-filmed copper surfaces as the test samples according to the method proposed by Barranger. Schneider has compared the wetting rate of copper oxidized in hydrogen peroxide using a wetting balance. Lowering of the concentration of the rosin itself in the solvent down to 12–20% wt/vol was claimed to provide a more stable soldering system in that loss of solvent by evaporation and the resultant changes in flux viscosity were minimized. The smaller weight per unit area of flux then deposited was a lesser thermal barrier to the solder wave allowing higher conveyor speeds. This aspect was also studied with a surface-tension balance by Drummond et al.

Inorganic fluxes

The common basis for inorganic fluxes is zinc chloride and a wide variety of formulations of this compound with other halides or salts is used commercially. Ammonium chloride is a common additive to increase activity and studies of the influence of this and other chlorides on the electrochemical cell formed at the solder/flux/basis junction have been made. The grey band or 'halo' formed beneath the flux ahead of the advancing solder was found to contain tin but no lead, by microprobe analysis, though laboratory studies showed that lead could also be deposited by chemical reactions.

It is essential to make use of very aggressive fluxes when soldering relatively inert materials or those with refractory oxide films, so that for stainless steel either a zinc chloride basis flux perhaps enhanced by the presence of free hydrochloric acid is used, or orthophosphoric acid. The latter type requires preheating to above 200°C in order to become sufficiently active, so that a number of different formulations have been devised to improve such fluxes, one example being the addition of copper or copper salts. In a similar manner, fluxes to aid in the wetting of aluminium have to be able to prevent the re-formation of the alumina surface film once it has been disrupted.
and fluorine-containing fluxes are often used with perhaps the addition of a metal salt (e.g., of zinc or cadmium) to promote wetting by the solder.\textsuperscript{176}

Flux application

The area where studies have been made on different methods of applying flux is that of the electronics industry where in-line fluxing precedes wave or drag soldering. In the early development of mechanized soldering of printed circuit board assemblies, rosin-based fluxes were made sufficiently fluid by adding solvent to allow application with brushes and rotating foam or felt rollers but later a wave of flux overflowing from a weir was used in a similar manner to the solder wave. This was found to deposit too much flux in certain cases and the foam-fluxing technique was thus developed in which a special formulation gives a stable foam of given bubble size when it overflows from a weir. This idea has persisted and organic water-based fluxes which can be foamed are now also available. However, the ability to give a stable foam is not necessarily consistent with a formulation having good fluxing properties. Davy\textsuperscript{177} has described an installation in which the liquid flux is applied in accurately controlled amounts by an airless spraying technique and he claims that the flux film is thin enough to allow the preheating stage before wave soldering, as required in most systems, to be eliminated. A commercial development which is aimed at making line control more simple is the incorporation in many wave-soldering machines of an automatic flux specific gravity control system to eliminate the manual testing and make-up procedure as formerly operated.

The increasing use of solder creams (i.e., solder powder–flux mixtures) has led to commercial research on devising thixotropic mixtures with good silk-screening properties for application to closely defined areas, for example. Clearly, the incorporation of properties of a physical nature will influence the chemical formulation providing the fluxing activity. A number of general papers have been published claiming the advantages of preplacing solder together with the flux in the form of solder cream or paste.\textsuperscript{178} Schoenthaler\textsuperscript{179} has identified some of the important factors in solder-cream performance.

Flux-residue removal

Rosin–basis fluxes were originally advocated for use in electronics and electrical assembly work because they were essentially non-corrosive and residues could be left on the soldered assembly. However, this required a limit to be set on the content of halide activator present in the flux (for example, 0.5%, based on the solids content, measured as chlorine, as laid down in BS 441:1964) to avoid possible insulation–resistance degradation or even corrosion. The increased use of conformal coatings on printed circuit assemblies required that all flux residues should first be removed before coating and organic–solvent systems were commonly installed for this purpose. The use of boiling fluorocarbon–alcohol mixtures was discussed by Clementson\textsuperscript{180} and one such compound is trichlorotrifluoroethane (FC-113).\textsuperscript{181} Kenyon\textsuperscript{182} has studied the efficiency of removal with different solvents of the residues of activated rosin fluxes. More recently, aqueous detergent processes have been devised for the removal of rosin residues and the lower cost involved is clearly important together with the very low residual contamination levels achievable.\textsuperscript{183} The latter aspect and the possible lowering of insulation resistance of certain epoxy–glass printed circuit boards by absorption of the aqueous cleaning solution, was studied by Turbini et al.\textsuperscript{184}

The chemistry of water–based fluxes and the influence of this factor on the insulation resistance of circuit boards after cleaning was studied by Brous and Turnbull.\textsuperscript{185} The advent of water–based organic fluxes led to the need for aqueous detergent washing systems and for components that could be exposed to hot alkaline water without suffering degradation in characteristics. Anderson\textsuperscript{186} studied the effect of different cleaning treatments for water–soluble flux residues on insulation resistance; the efficacy of these fluxes was discussed by Scheussler.\textsuperscript{187} The nature of flux residues after they have been subjected to heating during soldering and their reaction with different organic or aqueous cleaning agents has been examined in some detail by Casperson\textsuperscript{188} and the trend in cleaning systems has been towards a water–based system which is universal for all types of flux residues.

The importance of controlling the quality of the water used in these systems has been stressed\textsuperscript{189} and this and other aspects of flux–residue removal are discussed below in the section concerned with quality control in the soldering assembly process. The comparison of the use of tap and deionized water in the neutralization of inorganic or organic water–soluble flux residues by chelating agents has also been studied by Ellis\textsuperscript{190} using an instrument to measure the rate at which the residues are dissolved in a dynamic washing process.

With regard to the equipment available commercially for in-line printed circuit board cleaning, the effectiveness of ionic–residue removal in comparison with the cost of operating the cleaning process has been the subject of many presentations, for example, those by Bester and Titus\textsuperscript{191} and Kenyon and Daly.\textsuperscript{144} It is anticipated that automatic in-line cleaning will increase in usage irrespective of whether an organic solvent or water–detergent medium is employed, but the latter will be related to the availability of compatible components.\textsuperscript{143}

**SURFACE PREPARATION**

Because soldering fluxes are relatively weak in their chemical reactivity, especially those based on rosin used in most electronics soldering, the presence of surface oxide and similar films is detrimental to wetting by the solder. With few exceptions, therefore, surfaces require to be cleaned, so that they are free of grease or oxide.

Whereas for engineering assemblies, mechanical preparation such as machining or filing can be an adequate surface preparation, especially when strongly acidic fluxes are to be used, for electrical and electronics assemblies, usually only weak fluxes are allowable though components may
have to remain readily solderable after storage for a few or many months. To achieve this, most component surfaces are provided with a protective coating and it is the nature of these coatings that has been the subject of much research work and of guidance documents.219,220

Butt1,94 studied for uncoated copper and a variety of copper alloys, the deterioration of solderability with time (spread test and dip test). The order of merit of solderability after a given aging period was found to be different to that for contact resistance though it might be assumed that both properties are related to surface condition. In the electronics industry, the copper tracks and pads on printed circuit boards are sometimes cleaned mechanically or chemically and then protected against oxidation by use of a lacquer film. This lacquer is traditionally rosin-based in nature but the non-rosin organic-type flux recently developed is also used for protection of circuit boards.195 Chemical passivation treatments for copper using benzo triazole or imidazole have also been studied as protective treatments;196-198 and benzo triazole as a means of inducing different degrees of solderability on copper. In another work McCarthy et al.198 showed the importance of closely controlling the rinsing operation after acid etching in order to obtain a reproducible level of solderability. Tomes199 demonstrated by electron microscopy that mechanical brushing or jet blasting can entrap contaminants below the surface by causing the soft copper to flow and can result in poor adhesion of plated coatings or inferior solderability. Aggeton and Shaw200 stated that contamination of the surface by passivation films containing chromium, as well as embedded abrasive, can also degrade solderability. Outgassing during soldering from plated-through holes in circuit boards is, according to Luke,201 most often caused by inadequate preparation of the holes before sensitizing and plating, see also section 'Quality assurance' below.

In considering the use of metallic coatings to improve or retain solderability, the author202 and other workers have studied the solderability of different protective coatings as a function of storage time under various conditions. Broyer203 confirmed that hot dipping was superior to the others included in his test programme, thus confirming earlier work by Thwaites,13 and Rothschild reached the same conclusion.204 Pure tin has been widely used but the conventional matt plating has generally been replaced by bright as-plated deposits on circuit boards and component terminations but such deposits may be liable to whisker growth. Zakrzayek205 has published results of studies on this problem and listed the possible routes for reducing the likelihood of whiskers growing. The inclusion of organic materials in bright-tin plating has been studied by Colen,206 who claimed that the organic compounds could vaporize and outgas resulting in porous soldered joints. This effect had been reported earlier for certain types of gold plating28 and by de Vore.207 It is partly these problems that has persuaded many consumers to use electro deposited coatings of 63Sn-37Pb alloy and recent trends have been to fuse momentarily such coatings ('reflow' or 'flow-melt').208 This process improves the appearance and solderability and ensures that the substrate has been wetted by the solder coating, and is advocated for aerospace applications.209 Kingsley210 discussed the merits of the so-called ref lowing process and pointed out that at the sharp edges of plated-through holes, surface tension in the liquid solder coating may cause it to flow away from the edge to leave a thin coating that can subsequently cause poor solderability. This was also investigated by Dunn,211 who advocated a two-stage oil-bath reflow process. A reflowing procedure also has the effect of removing any tin-lead plating overhanging the edge of conductors that otherwise can break away as slivers of metal and possibly cause short circuits.212 The oscillation of a tin-lead plated printed circuit board during its time of immersion in a bath of hot oil to fuse the coating helps to maintain a uniform coating thickness, according to Durrant.213

The printed circuit board coating process that has seen the fastest development is that of hot-air involving in which the initial coating of 63Sn-37Pb solder is applied by hot dipping the board in a bath of molten solder after flux application; the board is then withdrawn vertically between planar jets of hot air to produce the desired and uniform thickness of coating and to remove solder from metallized through holes (Fig. 6). Rehbach214 pointed out that this process was less time consuming and hence more cost effective than plating solder followed by a reflowing procedure. The relations between variables including air velocity, temperature, and pressure, wiper angle, and the resultant coating thickness were studied by Schoenthaler215 and Smith and Walls217 and were part of an Institute of Printed Circuits (USA) programme to compare coating-thickness distribution on plated and reflowed, or solder-dipped and levelling, printed circuit boards.218 Muller-Ensslin219 advocated the use of air 'knives' on horizontally positioned boards, the excess solder that is removed not being returned to the solder bath as in the vertical system. Circuit board production rates of about 100 per hour for

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plating was proposed as a cheaper substitute for gold by Bader, while tin-cobalt alloy electrolec has been suggested as being potentially superior in commercial practice to tin-nickel.

Coatings based on tin are relatively near their melting point at room temperature on the absolute-temperature scale so it is not surprising that solid-state diffusion at room or slightly elevated temperatures leads to significant intermetallic-compound growth at the coating/basis interface. This phenomenon has been studied in detail by many investigators and some of the results are shown in Fig. 7. Scott and Warwick found that the most effective barrier layer to prevent the reaction of tin coatings and, for example, copper was a thin layer of iron. Also, nickel, which is commonly proposed as a barrier to prevent the migration of zinc out of brass, forms intermetallic compounds as rapidly as copper at 100°C and above. Davis et al. have described studies demonstrating the deleterious effect of interfacial compound layer growth and hence loss of thickness of tin coating on solderability.

The above demonstrates that the emphasis on precoating as a means of ensuring high levels of solderability has been largely concerned with the use of near-eutectic solder applied by hot dipping or plating followed by fusion, to achieve a good wetting of, and metallurgical bond to, the basis metal. Such techniques have become viable largely owing to the great improvement in the quality and temperature resistance of printed circuit board materials in recent years.

Coatings for printed circuit boards of an electroplated palladium-nickel alloy have also been developed and are claimed as having resistance to the etchants used for removing the surplus copper yet giving good solderability and protective action to the underlying copper conductors.

**SOLDERING PROCESSES**

By the word 'process' or 'method' is usually meant the means of applying the heat to the assembly to be soldered, but most often it is also taken to include the means of applying the solder (and perhaps the flux) and hence the physical form of the solder. Table 4 indicates the relations between heat source, flux, and solder for different joining operations.

The majority of the processes are briefly described by the method of heating and the ensuing descriptions of developments in the last decade are therefore divided according to this classification. The one entirely new heating method to have been developed in this period is that of vapour-phase or condensation soldering, currently used for certain types of printed circuit board assemblies (see below). A general description of the various methods of heating different assemblies has been published recently.

**Soldering irons**

The use of soldering irons and manual soldering operations are still mandatory for certain as-
Table 5 Size of braided copper tapes for desoldering

<table>
<thead>
<tr>
<th>Pad dia., mm</th>
<th>Width of braid, mm</th>
<th>Recommended soldering iron power, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.65</td>
<td>30-40</td>
</tr>
<tr>
<td>1.5-3</td>
<td>1.25</td>
<td>40-50</td>
</tr>
<tr>
<td>3-4.8</td>
<td>2.0</td>
<td>50-60</td>
</tr>
<tr>
<td>4.8</td>
<td>2.5</td>
<td>60-70</td>
</tr>
<tr>
<td>Terminals</td>
<td>3.3</td>
<td>60-70</td>
</tr>
<tr>
<td>Large terminals</td>
<td>4.8</td>
<td>100-150</td>
</tr>
</tbody>
</table>

*Table 5 Size of braided copper tapes for desoldering.
power, and the size of joint to be desoldered. Knox\textsuperscript{253} described the desoldering and removal of multicontact connectors.

Mass soldering

Mass soldering is generally taken to cover soldering processes in which a multitude of joints are soldered simultaneously by using some form of contact with a solder bath. Most commonly, wave soldering is implied but drag soldering or dipping in a bath are included. Technically, vapour-phase soldering could also be included, but for clarity it is dealt with as a separate procedure (see below).

In looking at the fundamentals of processes involving contact with a bath of molten solder, Klein Wassink\textsuperscript{254} and Verbeek\textsuperscript{255} carried out theoretical treatments of the heat-transfer aspects of the processes while Hersch\textsuperscript{241} examined heat-transfer requirements in plated-through holes to evaluate the viability of different soldering and desoldering methods.

Developments in equipment using solder baths include the use of a circular, rotating bath incorporating a fixed blade (Fig. 8) across the molten solder surface which continuously skims oxide and flux residues from the surface and deposits them in a peripheral annular receptacle.\textsuperscript{256}

Wave soldering

Karpel\textsuperscript{257} has demonstrated that there are now available a considerable number of commercial models of wave- and drag-soldering machines to cover different sizes of printed circuit boards and different scales of production. These machines vary in the minor details of design and construction but general developments to be noted include:

(i) a wider choice of wave shape and size
(ii) provision for deep waves for soldering extra-long terminations on boards, for example, back plane wiring pins
(iii) injection of oil into the wave or on the surface to improve wetting by the solder.\textsuperscript{258}

A departure from the conventional centrifugal pump to produce the wave system is one machine that employs an electromagnetic pump to produce a 'hollow' wave or moving sheet of liquid solder in the shape of an inverted catenary.\textsuperscript{260} This allows a greater length of component termination wire to protrude through the circuit board without danger of fouling the wave-forming spout, as might occur in the usual type of wave machine. Bernard\textsuperscript{261} has shown that the number of solder bridging defects can be reduced by using (i) an inclined conveyor to encourage drainage of solder back down the circuit boards and (ii) by incorporating oil injection into the solder wave.

A feature of most wave-soldering operations is that while sometimes the component termination wires are formed or bent to anchor the component mechanically in its locating holes in the circuit board, in many cases, for economic reasons, they are left straight and are placed in the appropriate holes in the circuit board. This gives rise to an initial tendency for the components to float on the molten solder wave as the solder rises in the holes in the board and this may on occasion displace

8 Rotating circular solder bath with fixed radial blade in surface to remove oxide continuously\textsuperscript{256} (Courtesy Sobilbraze Ltd)

them completely from their appointed location. Expanded polystyrene pressure pads and similar devices have often been employed on the component (upper) face of the assembly to hold them down. A recent development which overcomes this problem is the use of a specially formulated, high flash-point wax\textsuperscript{262} or other organic materials\textsuperscript{263,264} applied by a wave to the underside of the board, the component wires having been left at their original length. These projecting leads are now cut, by passage of the assemblies through high-speed tungsten carbide slitting discs, to the required height above the board surface (e.g. 2 mm) and finally the assembly is dewaxed in an oven and then wave soldered. This process is an alternative to the earlier procedure using a very deep solder wave to solder circuit terminations into place followed by cutting to length and a second, final wave-soldering operation to cover the cut wires.\textsuperscript{265} Without the second wave soldering, it is usually considered that there is a considerable risk of damage to the soldered joints possibly leading to field malfunction, especially if the slitting discs are not maintained in perfect condition. There is also the possibility of some corrosion occurring, of the termination basis metal (copper, nickel, iron, etc.) which is exposed when the lead is cut through. This procedure allows formal preheating of the assembly after cutting which can therefore be optimized. When the wax hold-down method may require major changes in the soldering parameters.

One of the difficulties in certain wave-soldering systems is the formation of 'icicles' or stalactites of solder from pins or wires which might result in electrical short circuits. One system of ensuring absence of these is to use a hot-air jet or
solder. The optimum angle of the air jet to the board was found to be 45° with a solder-wave temperature of 265°C and no effect of the type of flux used was found. The use of wave-soldering processes for solder alloys other than those of near-eutectic composition, normally employed in electronics assembly, has been discussed by Bud and Elliot. Higher melting point solders for use on electric-motor armatures and other items will influence the choice of materials of construction of the wave-soldering machine, while the use of wave soldering to join the terminations of coils has also been described.

In recent years more attention has been given to studies of the parameters of both the wave-soldering machine and the printed circuit board such as land and conductor geometry and size and literature such as this serves as a guide to those about to install this process. For example, the importance of pad shape and orientation with respect to the soldering direction has been clearly shown. Such studies are helped by the use of adequate instrumentation.

Concerning the soldering of integrated circuits or similar encapsulated devices on to printed circuit boards, hitherto, these have been reflow soldered individually on to the board (Fig. 9a) or alternatively, terminations of different configurations have been used in order that they may be inserted into holes in the circuit board ('dual-in-line' package) (Fig. 9b). A recent idea originating in Japan employs solder-coated metallised pads on each end of the miniature ceramic lead-less component (Fig. 9c), which is then attached by a heat-resistant adhesive in the appropriate position with the pads over the lands on the reverse (non-component) face of the printed circuit, and the complete assembly wave soldered in the usual way. This procedure, which would have not been considered previously because of the risk of heat damage to the components, permits components on both faces.

The cost effectiveness of changing from hand soldering to a mechanized system using a wave was illustrated by Pryor who quoted a possible increase in production of assemblies of over 60 times and described the steps to be considered in making a smooth changeover in process, including necessary alteration in printed circuit design and layout. Duffek also showed how assembly costs were reduced by wave soldering of dual-in-line packages on to circuit boards.

In the soldering of printed circuit board assemblies, there has been increasing use of solder resists to improve joint quality and decrease both the percentage of defects and solder consumption. Recent attention has concentrated on ultra-violet curable solder resist films.

In many soldering operations, especially in general engineering assembly work, jigs are required to hold the components in their correct relative position during soldering, especially when a conveyorized oven is employed. Silicon nitride is a material that fulfills the many requirements for a jig material while even certain high-grade plastics have been suggested.

**Reflow soldering**

While the majority of printed circuit board assemblies are soldered using wave- or drag-soldering techniques, another widely used mass-soldering technique is that of reflow soldering, that is, fusion of preplaced solder which may be printed on as cream or paste, or applied as a thick electroplated coating. These procedures may be applied to individual joints or in some cases can constitute another mass-soldering technique for a complete printed circuit assembly.

The most widely used heating methods for this process are immersion in hot fluid, radiant, electrical resistance (conduction), or induction heating. Leibfried and Stecher describe the use of an inert-atmosphere furnace for soldering thick-film circuits so that the need for a flux was obviated, and give results of tests of the strength of the resultant joints. The use of infra-red radiation, possibly in an inert nitrogen atmosphere, for soldering, using preplaced solder paste, was described by McManus. Employing the commonly used electrical induction heating technique using parallel-gap electrodes, Lampe studied the influence of various parameters on joint peel.
a normal, longitudinal current flow; \( b \) transverse heating current

10 Comparison of temperature profiles along length of electrical resistance heated soldering tool used for surface mounting of legs of flat packs\(^2\) (Courtesy Industrial and Scientific Conf. Management Inc., Chicago, Ill.)

strength of integrated circuits on printed circuit boards; a prerequisite was found to be a tin-lead coating of about 38–50 \( \mu \)m thickness on the boards when the leads were tin-plated with a 5–12 \( \mu \)m thick solder coating. For multiple lead reflow soldering using a device which both clamped the integrated circuit legs to the board as well as conducted heat into the joints, variations in geometry between the individual joints can give rise to different heating effects at each joint, especially if the energizing voltage is applied along the length of the heater bar. However, Engelmaier\(^2\) claimed that a transverse path for the heating current eliminated this problem and allowed use of an unlimited length of heater (Fig. 10). Capillo\(^2\) also discussed the use of electrical resistance heating for electronic-assembly work. Electrical resistance heating methods applied to the soldering of Nb–Ti/Cu matrix composites were described by Moorhead \( et al. \),\(^2\) who confirmed the detrimental effect on wetting and joint strength of any exposed superconductor–alloy strands. Other authors have reported on similar studies. Lindner\(^2\) discussed pulsed electrical resistance soldering of integrated circuit flat-packs on to film packs and claimed that if the operating parameters are chosen correctly, the quality and economics are better than are obtained with laser soldering and offer an economic alternative to the use of mass-soldered dual-in-line packages.

A new mass-soldering technique that is increasing in use is condensation soldering (vapour-phase soldering) developed first in 1973 (Ref. 288). In this method the vapour of a boiling heat-transfer fluid condenses on the surface of an electronic assembly containing solder preforms in such a manner that the transfer of the heat of condensation melts the solder, then on removal from the vapour the solder in the joints solidifies. The plant used is therefore almost identical to a conventional solvent vapour degreaser. The fluids typically are

flourinated compounds\(^2\) such as fluorinated pentapolyoxypropylene and perfluorotriamylamine which boil at 35 and 25 K, respectively, above the fusion point of 60Sn–40Pb solder. In a later development\(^2\) the loss of vapour of these expensive fluids from the plant is reduced by having a mixture of fluids such that the main heat-transfer vapour has above it a low-cost secondary vapour blanket of boiling point perhaps 150 K lower, which contains the vapour of the primary fluid. The fluid is also filtered to remove residues of fluid applied to the assembly.\(^2\) The plant is arranged so that the temperature of the water in the cooling coils for the secondary vapour blanket is sufficiently low for this liquid not to be returned to the primary boiling liquid sump in any great quantity. The mathematics of the heat transfer has been analysed by several workers.\(^2\)

Sufficient work has been carried out on the process and it has been used in production for enough applications\(^2\) such that a reasonable assurance can be given that the procedure can produce highly reliable soldered joints. Condra\(^2\) has described the use of condensation soldering for attaching leads to thick-film circuits. Spigarelli\(^2\) claims that since the vapour excludes air from the unit no flux is required for soldering. Figure 11 shows a typical thermal cycle curve for a large multilayer printed circuit board indicating that the heating cycle is fairly long compared with that in the conventional wave- or drag-soldering process.\(^2\) About 4.5 kW of electrical energy is required per kilogram of product soldered for the process to be viable. In the system using primary and secondary vapours, contact of the secondary vapour with the primary vapour at a higher temperature causes decomposition of the former with the liberation of some hydrochloric and some hydrofluoric acids that must be neutralized in the solvent recycling system to avoid corrosion of the plant. Clearly, this procedure is only applicable to the soldering of assemblies that can make use of preforms and are difficult to solder by normal methods. It has been used, however, for the fusion (reflowing) of electroplated coatings of tin-lead alloy on printed circuit boards\(^3\) and for solder-
Solder paste as a form of preplaced solder and flux is widely used in many 'preting' operations including solder-coated areas on printed circuit boards in which the paste is reflow soldered, and the relation between particle size, viscosity of the paste, etc., and the defined area of melted solder was demonstrated by Lee.302 Carter303 described the efficiency of soldering processes using solder paste. Preforms or pastes can also be used in conjunction with hot gas jet heating in micro-electronic devices.304

For convenience, soldering processes requiring the preplacement of solder and flux at the joint will be discussed briefly in this section. For example, for the connection of flexible leads to each other or to pins on circuit boards, solder 'sleeves' are quite widely used. In these devices, rings of solder (flux cored) are located within a plastic sleeve into the two ends of which the terminations are inserted. Sufficient heat is applied with a hot-air jet to melt the solder ring and effect the joining as well as shrink the sleeve over the joint area to produce a hermetic seal.305 The use of preformed rings, washers, and pellets was reviewed by White306 and Mackay,307 and examples of their use are in the manufacture of trumpets and automotive windscreens, wiper mechanisms.308

Radio-frequency induction soldering is widely used for the soldering of many different engineering assemblies with solder preforms, but very little literature has been published on the subject. Design of the induction coil is of vital importance in obtaining uniform and adequate heating and this aspect has been discussed in some detail.310,311 Hot-air reflow-soldering processes (Fig. 12) have been described for specific applications340,312 including the attachment of handles to pewterware drinking vessels.

A novel procedure which may be said to come within the technical category of reflow soldering, forms a substitute for demountable mechanical plug and socket systems between two assemblies, and consists of rigid pins on the assemblies which are inserted into socket filled metal containers.313 A revised method described by Getten et al.313 proposes an interconnecting board having solder-filled plated-through holes so that the pins on the two assemblies to be connected may be inserted from the opposing faces of this intermediate board: the solder in the holes is melted by the presence of electrical-resistance heaters built into the interconnecting board. Clearly, such a system is relatively costly and would be engineered for a specific application. Getten et al. claim that the rate at which the pins are inserted or withdrawn is critical, but the system appears to allow up to 20 de-soldering and resoldering cycles. The system described included a new flux containing 4 wt-% sulphuric acid in an oxidized homopolymer of polyethylene with the addition of fine silica to increase viscosity. It was also found necessary to use a solder alloy of low melting point and that recommended was 52.5Bi-32Pb-15.5Sn with a melting point at 96°C.

Ultrasonic soldering

This is a special technique mostly used for facilitating the wetting by solder of aluminium, but also effectively used on difficult materials including silicon, glass, and ceramics. Little has been published on the latter aspects.

The soldering of aluminium has always been claimed as difficult and one means of dislodging the tough alumina film on the surface is by ultrasonic vibrations, in which case chemical fluxes are not required.314,315 The influence of ultrasonics on the surface tension of aluminium and copper against molten tin-lead and zinc-aluminium alloys was studied by Antonevich316 in an attempt better to understand the wetting process. Power requirements and capillary joint penetration were monitored and it was demonstrated that the power to achieve cavitation in a tin-lead solder was very high, thus reducing the usefulness of the technique. Also, for effective cavitation the transducers must be in close proximity to the workpiece and the solder bath should be shallow. Figure 13 shows the minimum displacement of a soldering-iron tip at 40 kHz to effect wetting of copper by 60Sn-40Pb

![Graph showing relationship between soldering temperature and minimum displacement](image_url)

13 Relation between soldering temperature and minimum displacement of soldering-iron tip by ultrasonic transducer to achieve wetting of Cu by 60Sn-40Pb solder316

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solder. The use of a solder bath of semicylindrical shape allows a greater density of transducers to be fitted than does the normal rectangular shape and thus increases the possible power input.\textsuperscript{317} Lystrup\textsuperscript{318} also studied the geometry of an ultrasonic bath using both zinc- and tin-base solders. Erosion of the transducer horns in the molten solder was shown to affect the performance and the solder composition, but temperature variations had no influence on the ultrasonic effect.

Generally, for difficult materials, ultrasonic vibrations are used to eliminate or minimize the use of fluxes, but the potential of the technique has not yet been fully investigated or realized.

QUALITY ASSURANCE

In recent years there has been a dramatic increase in the attention paid to the reliability of electronic and other assemblies in service. This is in part due to the present high cost of fault detection and repair in the field.\textsuperscript{319} The importance of detailed consideration of the materials and processes to be used in a production scheme has been stated by the present author.\textsuperscript{320,321} A mnemonic - SECA - was suggested to remind engineers of the basic stages of Specification of materials, processes, etc., Evaluation of the incoming goods, Control of the processes, and finally, Assessment of the quality of product. Of these, the first has overriding importance since use of the incorrect materials or non-optimum process conditions leads to a decrease in quality and reliability of the soldered assembly.

Wajntraub,\textsuperscript{322} Leonida,\textsuperscript{323} Bernard,\textsuperscript{324} and Duhl et al.\textsuperscript{325} have all described the relation between the parameters of the soldering process. The incidence of types of defects was related to flux type by McElwee,\textsuperscript{326} Pascoe\textsuperscript{327} described a tabular system for relating specific faults in soldered assemblies to their cause. The relation between choice of flux and soldered joint defect incidence was shown by Cassidy and Lin.\textsuperscript{328} Strauss et al.\textsuperscript{329} described the application of university research facilities to the solution of soldering problems occurring in industry, particularly the extreme usefulness of the scanning electron microscope. Troubleshooting in the printed circuit manufacturing industry in general was the theme of a photographic guide by Shamilt.\textsuperscript{330} The metallurgy of soldered joints for reliable operation in space applications was studied by Hindmarsh,\textsuperscript{331} Dunn,\textsuperscript{332,333} and Kunde.\textsuperscript{334} Aspects of designing for reliability in domestic electric-motor controls were described by Dryden,\textsuperscript{335} who demonstrated a ten-times increase in reliability of machine-made over hand soldered joints. Zimmerman\textsuperscript{336} highlighted the importance of written instructions in wave-soldering assembly operations. One system of recording the type and grade of defect has been disclosed;\textsuperscript{337} the Post Office (UK) also classified soldered-assembly defects at three levels depending on whether the defect will cause immediate failure of operations, a potential service failure, or whether it is not of significant importance.\textsuperscript{338} A handbook that contains preferred manual-soldering techniques for space vehicles was compiled by Dunn\textsuperscript{339} and is widely referred to by aerospace contractors. The American Institute of Printed Circuits\textsuperscript{340,341} and the US Department of Defense\textsuperscript{342} have also published documents on this subject. The causes of various defects in wave-soldered assemblies have also been enumerated by the IPC. One defect seen on soldered printed circuit assemblies is the presence of gas blow-holes in the fillet of solder or observed in metallographic cross-sections of plated-through holes. Scheulessier\textsuperscript{343} has described how the nature of the gas in the hole can be analysed by gas chromatography and mass spectrometry techniques to determine the source of gas; Lea\textsuperscript{344} has also published a note on this. Bulwitz\textsuperscript{345} has suggested causes and cures of the phenomenon such as entrapped flux and outgassing of moisture or processing chemicals, and strongly advocates close control over all etching and electroplating operations. The reliability of soldered assemblies under thermal-cycling conditions, typical of many electronic applications such as aerospace, was the subject of work by Messner and Lassen\textsuperscript{346} and Schoomaker and Poyer\textsuperscript{347} for multilayer boards, and by Lang et al.\textsuperscript{348} for power transistors.

Specific aspects of quality control that have been considered are visual inspection of soldered joints, metallographic examination of joints combined with coating-thickness measurements, testing components for solderability, and flux-residue determination.

Much has been written on the subject of the reliability of soldered joints made to gold plated electronic components and recent example papers by Crouch\textsuperscript{349} and Kehrer and Wenzel. Problems of the cracking of soldered joints by a thermal-fatigue process have been mentioned above. A joint-failure mechanism specific to PTFE-filled coaxial radio-frequency semirigid cables was studied by Fletcher,\textsuperscript{351} who showed that the thermal expansion of this dielectric material was the primary cause of fracture as well as the presence of gold–tin intermetallic layers on gold-plated components. The poor wettability caused by excessive inward diffusion of precious-metal–glass layers on thick-film circuits when temperature and time are inadequately controlled in the heat treatment was a point made by Allison and Provance.\textsuperscript{352}

Regarding the quality of printed circuit boards, Tissier\textsuperscript{353} and Clarmo\textsuperscript{354} made recommendations on the preferred means of storing boards to prevent loss of solderability before they are used. Wray\textsuperscript{355} used surface analytical techniques to study the growth of films on tin–lead plated surfaces; these films can lead to a decrease in solderability. Pensek\textsuperscript{356} showed that a blue colouration of tin–lead plating that can develop during storage of circuit boards is a thin film of tin oxide which diffracts light and is only formed on chemically ultraclean surfaces. Control of the quality (i.e., impurity levels) of the solder is the subject of a simple testing method proposed by Becker\textsuperscript{357} et al. Several other papers on the effects and control of impurities have been published.\textsuperscript{18,45,358}

Looking outside the electronics industry, very little has been published but Gibertson\textsuperscript{359} examined the factors involved in controlling the quality of heat exchangers and Edwards\textsuperscript{360} showed
14 Good wetting of component termination lead but dewetting of solder on circuit board pad resulting in inadequate size of solder fillet the importance of controlling joint gap in the installation of soldered capillary-pipe joints.

Because of the known incidence of liquid-metal embrittlement (LME) by certain liquid metals, for example, on stressed steel components, engineering applications of soldering are often restricted to some standards (e.g. Defence) to use on low tensile-strength steels to avoid any risk of premature failure. Nicholas and Old362 have reviewed the subject of LME in some detail but there are very few documented cases of failures associated with the use of soldered joints.

Visual inspection

Although many automatic systems for the on-line checking of the electrical functioning of soldered printed circuit assemblies are being developed, currently there is no way of indicating the quality of a soldered joint other than by a visual examination and assessment. Clearly, an electrical function test will indicate short circuits or the complete absence of a connection. Attempts are being made, however, to use scanning laser beams to identify sub-tiny examination... A visual examination the aim is to achieve meaningful assessment based on the accept/reject criteria that are specified and photographic guides on the quality of joints have been produced364-368 to help with this task (Fig. 14). There is a continuing discussion on whether it is necessary to have a fillet of solder on the top side (component face) of a plated-through hole as an indication of satisfactory joint quality369 and factors controlling the capillary rise of solder in through-holes during wave soldering were discussed by Tamura et al.370 Gadzinski371 claims that it is not essential and Keller372 pointed out that it created added cost to the product. Keller and Waszczak373 and Becker374 concluded that there is no evidence that a completely filled hole corresponds to a better joint quality or reliability and Woodward’s375 studies tended to confirm this view. The move towards elimination of costly inspection and rework by a greater input of effort in the planning and operational control has been discussed by Keller et al.376 and this is in line with the present author’s idea of the SECA system mentioned above. Ponwitz377 also stated that attention to detail at all the earlier stages can lead to a minimal requirement for inspection of both sides of the final printed circuit assembly. Aspects of the repair of defective joints have been detailed by Lanning,375 Kingsley,379 and Davies;380 and the statement that ‘prevention of defects is better than curing’ them, has been made.381 The use of braided copper wires to remove solder before detaching a component was described by Strauss382 and McBride.383

Reasons for ‘pimples’ in soldered joints383 and for ‘grittiness’ or gas inclusions in solder coatings and joints384 have also been reviewed. The scanning electron microscope was the chief tool for these investigations and for the studies made by Thwaites385 and Lampe and Brewer386 in relating outgassing and solder splatter to discontinuous copper plating in the holes. Examination of the quality of plated-through holes by X-ray techniques has also been employed387 (Fig. 15). The presence of pimples on solder fillets was shown by Steen388 to be caused by the protuberance of primary lead dendrites from the surface of the

15 Protrusions on a surface of plated-through hole shown b to be Cu owing to poor surface preparation; SEM ×1000
solder, presumably as the lower melting eutectic drained down into the hole.

Metallographic examination

Metallographic examination is used as a destructive method of checking the coating thickness and continuity, for example, plated-through holes. A measuring microscope can be linked to a computer terminal to aid in assessing the data from the examination, and polarization or interference contrast lenses may be used to aid in differentiation between layers. However, the most widely used tool for surface examinations is the scanning electron microscope. This is particularly useful for microcircuit work because of its high depth of field at magnifications of ×100 or so, (Fig. 17). Reference was made to the use of this instrument in several papers.

Solderability testing

The testing of electronic components for solderability, i.e., ease of soldering, has become a recognized part of quality control in a production scheme. The author and others have reviewed the various test methods available and the trend is towards making the surface-tension balance the instrument to be relied on in the future. However, Barranger has developed the meniscus-rise test, which is also included in a French standard for soldering materials and tests. Flot et al. have discussed the use of a computer-aided balance for routine work. Comparisons have been made of the values obtained for solderability by different techniques on materials of given and controlled solderability, namely, copper in various states of passivation and on tin and tin-lead plated copper wires. The results were correlated with actual wave-soldering tests (Fig. 18).

Possible improvements to the rotary dip solder bath test for printed circuit boards were described by Klein Sellink. Concerning the use of a surface-tension balance, a draft IEC document is in preparation to cover the procedure and interpretation of the results (Fig. 19). Schouten

17 Detail of fatigue crack in solder fillet after assembly was subjected to thermal cycling; ×30

18 Relation between wetting time in rotary-dip solderability test and in production wave-soldering machine with identical temperature and flux; material was passivated Cu wire
19 Different values that may be taken from curve obtained from surface-tension (wetting) balance solderability tester: wetting time $T$ (at zero force) or $T_B$ (at buoyancy point), or $T/3$ or $T/2$ (at $1/3$ maximum wetting force); maximum wetting force $W$; slope = wetting rate

described a new mathematical treatment of the resultant curves such that values obtained below a certain limit indicated inadequate solderability. Allen and George$^{438}$ have described the methods used in their company for standardization of the method and Ling$^{439}$ has described a variation of the balance to give an indication of wetting speed. The scanning of the solderability of a surface, using the surface-tension balance, was suggested by Becker$^{410}$ to give more objective statistical values. Solderability testing of microcircuits requires special consideration because of the size factor.$^{411,412}$ Considering applications of wetting tests outside of the electronics industry, Shawki and Hanna$^{413}$ described detailed studies using the surface-tension balance of the wetting of steel by tin, zinc, and their alloys in relation to hot-dip coatings and found a minimum contact angle with an alloy of 60Sn-40Zn. Allen$^{414}$ suggested that Arrhenius plots derived from surface-tension-balance curves could be used to give activation energies for soldering fluxes. The use of solderability tests to compare the wetting properties of different solder alloys and the effects of impurities was described above in the section 'Solder alloys'. The solderability of plated-through holes in printed circuit boards has been discussed by several workers because of the influence of solderability on the capillary rise of solder in the holes and Becker$^{415}$ has described the use of the globule test for this purpose. The solderability of different surface finishes was the subject of papers by MacKay$^{416}$ and Ackroyd and MacKay.$^{417}$

It is useful to specify some form of accelerated aging treatment of components before solderability testing to attempt to determine the degree of degradation that is likely to occur during storage and Ackroyd$^{418}$ has reviewed some of the treatments currently used. A new test involving metered injection of oxygen into saturated steam as the environment was developed by Wilson$^{419}$ and this was subsequently included in British Standard 9785. The influence of dry and steam accelerated aging in conjunction with the normally applied 'burn-in' treatments for certain components was examined by Dhaussy et al.$^{420}$ Using the surface-tension balance to measure contact angles they discussed the problems of sampling and variations between batches of nominally identical components. Okamoto et al.$^{43}$ showed the relation between surface-oxidation state of the conductors on circuit boards with soldering time and temperature.

**Flux-residue assessment**

Whereas it was formerly considered that only rosin-based fluxes with a strictly limited added activator level were allowable for electronics use in order to prevent either a decrease in insulation resistance or positive corrosion, there is a strong move to use more corrosive fluxes to reduce problems of variable solderability of components. Lethridge$^{421}$ has discussed corrosion resulting from flux residues in general terms. The residues of such fluxes need to be removed (see section 'Fluxes' above) and many papers have been published concerning the measurement of ionic residues from fluxes after their removal. Insulation-resistance measurements of standard printed circuit board patterns and test combs after contact with soldering fluxes have been made in most of these investigations, many of which were discussed above in the section 'Fluxes'. The effect of thermal cycling in relation to the fluxes used has been described by Jol,$^{422}$ Turnbull,$^{423}$ and Schouten.$^{424}$ Zado$^{425}$ found that under very humid conditions anodic corrosion of solder in a joint could occur. It must be stressed that this is only a selection of the many papers produced in the past decade on the topic of flux residues, their removal and resultant residues. The introduction of water-based organic acid fluxes has been claimed to lead not only to fewer soldering defects but also to lower levels of ionic contamination after the cleaning treatment.$^{426,427}$

Various instrumental methods are available for measuring the presence of ionic residues and these have been discussed by Martz$^{428}$ and Ellis.$^{429}$ The latter discussed the use of a processor-linked monitoring system while Allen and George$^{430}$ recorded their experiences with a different type of commercial instrument based on the dynamic conductivity monitor.$^{430}$ In using aqueous fluxes for the mass soldering of electronic assemblies, it was claimed by Ingraham$^{431}$ that the quality of the water used to clean flux residues from the boards after soldering should be carefully monitored.

Actual corrosion problems in the electronics industry appear to be rare, but Dunn and Chandler$^{432}$ showed that the presence of some halide activators in rosin fluxes could give rise to stress corrosion of materials such as Kovar (Ni-Fe-Co). Ray$^{433}$ has examined potential corrosion problems in transistors.

The absorption of flux components such as halide ions by printed circuit board materials has been examined by radioactive tracer techniques and found to be least for Teflon.$^{433}$

It is appropriate to mention that some effort has been made towards soldering without the use of a flux to overcome flux-residue problems and most work has concentrated on soldering in an oxygen-free inert atmosphere or a vacuum.$^{434}$

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HEALTH AND SAFETY

All industrial plants, in the western world particularly, have become highly concerned with the protection of personnel against hazards at their place of employment. In the field of soldering technology the hazards may be divided into those caused by heat or those caused by chemical risks either as liquid or vapour. The possible effects of rosin-flux fume in causing chest complaints in later life have been described by Burge and Lunau and the measurement of toxic formaldehyde as a breakdown product does not seem to be necessarily related to this effect. The lead content of the atmosphere near soldering operations has been discussed by Wevers and Warren for high-temperature soldering of tinplate cans with lead-rich solders, and for all soldering operations by van der Molen. The risk of excessive lead inhalation during normal soldering appears to be minimal to non-existent. Kosmac described methods of extraction of fumes and gases in the soldering workplace. Rubin described a new non-rosin organic flux which gave less fume during soldering and hence reduced risks to health. Similar considerations have been given to other fumes that may occur in soldering processes such as heat-transfer vapour may enter the environment and Turbini and Zado have discussed the necessary safety precautions to be taken with such processes. A number of governmental and other documents are available regarding threshold limits and workplace safety.

STANDARDIZATION

A number of national or international standards concerned with soldering technology have been either newly issued or reviewed during the past ten years. Table 6 is not comprehensive, but lists the more important of those appearing in the UK, France, the FRG, Japan, Sweden, and the USA, as well as international work. This shows the increased activity in standardization work that has largely been related to the rapid growth of the electronics industry.

In addition to the standards listed within different categories, others are available or have appeared, related to the soldering process and some of these, concerned with preferred techniques for producing highly reliable joints, have been quoted. Standards about inspection criteria are frequently generated in-house but the US Dept of Defense recently published one such document which was similar, but of wider scope, to the British Post Office quality-assurance publications.

SUMMARY

Table 1 gives an indication of the rate at which technical publications on soldering technology hav-
increased in number. Despite industrial and economic recessions the electronics industry has maintained a high level of research and development work and it is believed that the literature surveyed herein probably represents only a small fraction of all the in-house studies undertaken; the results of which have not been published. The increasing miniaturization of all components has aggravated many production problems and has required much stricter quality controls than in former years. This has led to the use of relatively sophisticated tools, such as the scanning electron microscope, Auger analysis, and infra-red spectrometry, being employed in much of the work. The increasing application of scientific method to studies of the soldering process, especially in the electronics industry, seems likely to continue steadily in the foreseeable future and there is little indication of any major alternative to soft soldering as the mass-production technique for making connections between electronic components.

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