Special Feature

COPING WITH LEAD-FREE SOLDER

BILL MOONEY

What are the alternatives to using lead-based solder when it is banned internationally in 2006?

LEAD will soon be phased out of electronics, but there is no "drop-in" replacement for our trusty old 60/40 rosin-cored solder. Worse still, the new lead-free technology is not fully compatible with traditional lead based components.

Lead (Pb) will be banned internationally in most electronics products from 2006. The pace of the transfer to a lead-free electronics industry has quickened and several manufacturers have already converted to lead-free production.

This action comes under the Restriction of Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE) EU directives and has already impacted on service engineers and some professional electronic workshops. But electronics hobbyists and many smaller workshops are largely unaware of the change and its consequences.

NOT SO SIMPLE

Unfortunately, the changeover will require more than simply reaching for the new Pb-free solder and dumping the old stuff. The legislation is far reaching and even threatens the use of colophony (rosin) – our favourite flux. Just in case that is not a big enough challenge there are also requirements for a low VOC (Volatile Organic Compounds) content and, of course, halide-free emissions.

The very components we buy and the printed circuit boards we use could soon be lead-free finished. The soldering characteristics will be different and will vary as no single finish yet dominates the market. Tin/silver (Sn/Ag) and tin/silver/copper (Sn/Ag/Cu), also gold/nickel (Au/Ni) bi-layer and Bismuth (Bi) alloys are examples, but development continues.

Other finishes such as 100% tin with its tin whisker-growth problems are also possible.

Rosin-cored TSC solder.

We might have expected good compatibility between lead-free solder and the lead-based finish on present components. But to add to our problems, even slight amounts of lead contamination have deleterious effects on lead-free technology. This finding is so important that separating the technologies is a priority for manufacturers. Rather than implement a gradual change, they must plan an expensive switchover to lead-free.

If you attempt to work on a cellphone, minidisk, PC etc. there is an increasing chance of it being lead-free. Repairing this with your trusty old 60/40 solder wire will definitely produce a less than perfect result.

We can learn to live with the best lead-free alloy available at this time namely tin/silver/copper (TSC); see later.

Other solders such as tin/zinc, tin/copper, bismuth containing alloys like tin/silver/bismuth and low melting aluminium formulations will further confuse the situation. Let alone the possibility of conductive adhesives, which are under development. Considering that soldered joints are the most common cause of circuit malfunction and that the best lead-free TSC solder is "not optimal"; we could be set for interesting times.

Table 1 shows the current solder choices for general electronic work.

ALLOY OPTIONS

The move to lead-free electronics has turned out to be very difficult. From a huge range of possibilities, over 200 alloys have reached the serious testing stage over the last 10 years. No trouble-free "drop-in" alternative to rosin-cored 60/40 tin/lead formulation has so far been produced.

As for the silver-loaded low melting point solder (LMP) favoured for surface mount (SM) production and hand soldering surface mount devices (SMDs) there is no alternative and we must learn to work with TSC. For commercial SM production the higher temperature can mean working under nitrogen gas to reduce oxidation.

The metallurgy of solder formulation is complex, involving dedicated laboratories for its development. For practical purposes its melting behaviour is fundamental.

Pure metals melt at a specific temperature, for example lead melts at 327°C and tin melts at 232°C. An alloy is a mixture of metals and its melting point is lower than the melting point of its components.

Table 1. Current solder choices for general electronic work

Alloy	*Melting point*	*Typical product*	*Comment*
60/40 Sn/**Pb**	188°C	Ersin Multicore 0.8mm	Traditional, widely used rosin-cored solder wire
62/36/2 Sn/**Pb**/Ag	179°C	Multicore Smart 0.5mm	Low Melting point (LMP) solder for SM work
95·5/3·8/0·7 Sn/Ag/Cu	217°C-220°C	Multicore Ecosol TSC 0·7mm wire (RS Components)	Target replacement for 60/40, mildly active rosin-free flux
95·5/4/0·5 Sn/Ag/Cu	217°C-220°C	Shenmao TSC 1mm wire TSC (Maplin)	Target replacement for 60/40 rosin mildly active flux
96·5/3·5 Sn/Ag	221°C	Multicore MX200 1.2mm wire (Maplin)	Active core, tough solder for mechanical work inc. jewellery, aluminium, stainless.

Eutectic alloys have specific proportions of each metal component and exhibit a sharp melting point. For example, the 63%/37% tin/lead eutectic melts at exactly 183°C. The more common 60/40 solder is slightly off the eutectic ratio and melts over a small temperature range in which it is "pasty", this improves the working properties. The pasty range, therefore, exists between an upper temperature referred to by metallurgists as the "Liquidus" (above which the alloy is fully liquid) and a lower "Solidus" temperature (below which the alloy is completely solid). The paste is a complex mixture of liquid eutectic and solid metal or metal compound crystals and is the stuff of metallurgy. Metallurgists use phase diagrams to describe these mixtures.

The choice of metal is determined by many factors, including cost, toxicity, chemical reactivity, melting point and its behaviour in alloys. In particular, a metal is required to melt at a temperature around 200°C and to have good affinity for other metals found on electronic components. The choice in order of diminishing toxicity is restricted to:

Lead (Pb) > silver (Ag) > antimony (Sb) > copper (Cu) > tin (Sn) > indium (In) > zinc (Zn) > bismuth (Bi)

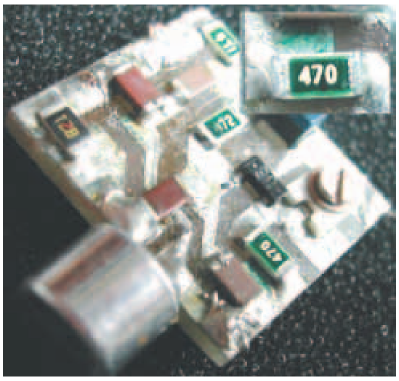


Fig.1. Use of SA (tin/silver) solder wire for a surface mount project.

Some of the best alloys found so far contain silver which can be a concern in landfills. Silver increases the surface tension of the solder, degrading its wetting properties. But it lowers the melting point and improves conductivity. Safer metals have inferior soldering behaviour or are expensive. Silver is about 200 times the cost of lead but small amounts are effective. Tin is 10 times more expensive than lead but the reduced life cycle processing costs (refining and disposal etc.) result in a similar solder price to the user.

GIVE IT SOME TSC

Tin/silver (SA) alloy wires have been around for some time but they have a higher melting point starting at 221°C and tend to have a reactive flux core. These have adequate wetting properties and are easy to use, even on aluminium and stainless steel with suitable flux. But the higher temperature required can make the soldering action sluggish and circuits must be solvent cleaned after use.

A typical SA product is Multicore MX200 18s.w.g. wire with a mildly active flux. This is a very useful product to have around for mechanical work, jewellery and even some heavy electronic contact work, but is not the best choice for light circuit work.

Workable ternary (three metals) alloys have resulted from a frenzy of research. For our purposes a tin/silver/copper alloy seems to be the closest we will get to a 60/40 replacement. This is often referred to as TSC or SAC (Sn/Ag/Cu). These are very near eutectic compositions such as 95·91% tin/3·42% silver/0·67% copper. Slight variants abound such as 95·5/3·8/0·7 (Sn/Ag/Cu).

All have initial melting temperatures in the range 217°C to 220°C and have slightly inferior wetting power compared to most lead-based solders. Typically, a 1mm TSC solder wire will contain about 3% of a synthetic non-corrosive flux core, but rosin-based variants are available at this time. The tin-based alloys are less lustrous than 60/40 solders and have a slight yellow/gold cast. They are also mechanically stronger than the lead based technology.

A big problem with the new alloys is their high melting temperatures. An increased melting point from about 188°C for 60/40 to about 220°C for the TSC may not seem too important, but above 230°C we are reaching the thermal limit for many support materials.

Breakdown of adhesives, de-lamination of copper tracks, cracking of component packages, breakdown of solder-masks and oxidation rates, all accelerate rapidly. For production this means even narrower process windows. But all of these effects impact on hand soldering, making the process that bit more problematic.

MAKING THE CHANGE

The author's first venture into lead-free consisted of populating a small surface mount circuit on a pre-tinned printed circuit board. This was a worse case test with the MX200 SA solder wire. LMP solder wire would normally be used for SMDs with a melting point some 42°C lower!

The higher melting temperature of the SA solder was immediately obvious. It took longer to achieve good solder flow and full wetting of the surfaces. Similarly, the joint cooled very fast. The tin/silver alloy was dull and lacked the brighter reflective finish of the traditional 60/40 solder. This appearance was in part due to lead contamination from the tinned p.c.b., see Fig.1.

This high temperature stress was positively cruel to the little SMDs. It is likely that over several tests, or if the circuit was subjected to temperature cycling, defects would appear. But for test purposes it was possible to produce an adequate working circuit with a lead-free solder.

The MX200 solder contains an active flux and after a few days, green salts (Fig.1) appeared in places. Experience has shown that this flux can lodge permanently inside components such as trim pots even after cleaning, leading to noisy unreliable circuits. With serious lead contamination, corrosive flux and high melting point solder stressing the chip components, this approach is not seriously recommended. The point is, **don't just grab the first lead-free product you see**.

BEST OPTION

The target 60/40 replacement is the TSC solder wire with a synthetic or rosin flux core. For the second test, the author selected a 95·5/3·8/0·7 TSC wire with rosin-free synthetic flux core. It was compared directly with 60/40 on clean new stripboard.

A 12W Antex iron was used with a standard iron coated bit. The bit was well tinned with tip cleaner and sponge before making the test. The tip cleaner was lead-based because there is currently no lead-free tip cleaner available.

The high melting point again resulted in just noticeably longer times to achieve solder flow. Unfortunately, the flux evaporated rapidly and wetting ceased before the solder flow was complete. Also, the underlying wetting characteristics of this alloy are inferior to the old 60/40. Given these negatives it could be expected that the results were not as good as we are used to, see Fig.2.

Fig.2. Comparing TSC lead-free solder to standard 60/40.

The TSC is generally inferior to the 60/40 reference standard. In all cases the joints have a "dirty" appearance with traces of slag-like deposits. Lead contamination from the tip cleaner was in part responsible for this behaviour. The poor wetting resulted in uneven edges of the solder mass. If we had no alternative, a circuit made in this way would work well enough, after reworking the odd "dry joint". But there is plenty of room for improvement.

LEARNING TO USE TSC

To achieve good results with TSC, the same good practice must be followed as for traditional solder. Particular issues to consider when using TSC can be summarised as follows:

1. Type and level of flux
2. Lead contamination
3. Iron power rating
4. Existing solder (for rework)
5. Component finish

The tests described above used 0·7mm TSC wire with a synthetic flux core, the preferred material from an ecological standpoint. But loss of flux and poor flux performance are responsible for the barely acceptable result. Stepping back in technology to a rosin-cored 1mm TSC wire (Shenmao) produced an excellent joint as shown in Fig.3.

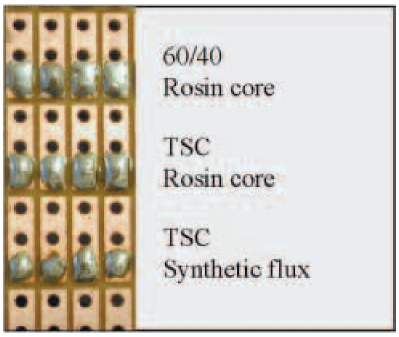


Fig.3. Comparing TSC solder wires with rosin and synthetic flux cores.

This clearly shows the power of rosin as a flux. For all practical purposes, this is as good as the rosin-cored 60/40. Although a close look at the 60/40 solder blobs reveals that they are slightly flatter due to better wetting of the copper by the lead-based alloy. The synthetic flux cored TSC test is repeated for comparison and again shows poor spreading.

FLUX PENS

A flux pen is an essential tool even when working with lead-based materials, but is probably indispensable in the lead-free world and certainly during the transitional period. In any case, the lead free solders have inherently poor wetting properties and need the support of a good flux. The rosin based pens give excellent wetting and do not necessarily require cleaning, as rosin is a very adequate finish.

The newer no-clean pens also work very well for enhancing the thinner TSC solder wires which have a low flux content. Thinner solder wires are preferable for modern leaded components to make perfect joints with ideal amounts of solder. For surface mount chips, thinner wire ensures the minimum solder loading. Intolerance to rosin fumes may dictate the use of a synthetic formulation, although a fume extractor is still advised.

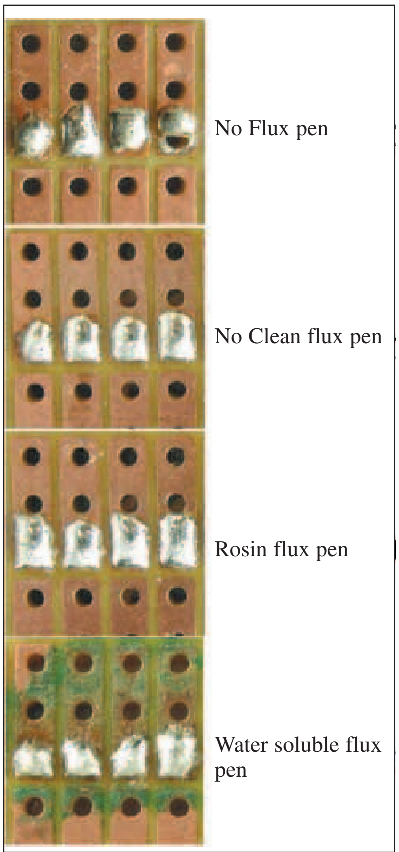


Fig.4. Comparing flux pens on 0·7mm TSC wire.

Two flux pens from Circuit Works were used by the author to test the effect on the performance of a 0·7mm synthetic-flux cored TSC wire, as shown in Fig.4.

Both products produced good wetting and clean solder pads from this low flux solder wire. Care is required when selecting flux pens as some are very corrosive. Fig.4 also shows the effect of a flux pen with a very corrosive water soluble flux a few hours after soldering.

These reactive materials give good rapid wetting but should be avoided for small component work. If in doubt, do a small test as above, looking for green copper salts on a permanently wet surface.

LEAD CONTAMINATION

Looking closer at even the best TSC result reveals another problem. Low levels of lead contamination interact with tin compounds to produce an uneven surface on the solder as it drops below the melting point. The tin compounds present in the lead-free solder are not soluble in the lead.

Lead-rich zones follow the hottest areas as the solder cools and therefore end up at the point where the iron tip was removed from the solder blob. This "phase" separation of solder produces a poor surface appearance, as shown in Fig.5.

Unfortunately this is not just skin deep. If strength tests were done on a number of lead-contaminated soldered joints the results would be disturbing. Contaminated joints are generally weaker and there is a wider spread in strength results, due to random zones of lead and tin compounds. Typical laboratory reports show that as little as 1% lead contamination can reduce joint strength by 75%.

0603, 0402 scale. Even the commercials can't cope with the new 0204 full stop sized chips.

DILUTED EFFECT

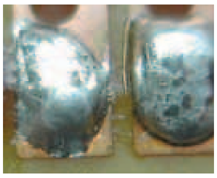
At this time, most lead probably comes from the component and p.c.b. finishes and from tip cleaners. Unfortunately, we will have to live with the lead-based component finish for some time.

Making a joint with TSC, then using a solderwick to strip the contaminated solder can reduce the lead level. The joint can then be remade with fresh TSC. This may be worthwhile in critical cases where reliability must be assured.

For the purist, lead contamination from printed circuit board coatings can also be diluted by repeatedly adding TSC solder wire and removing it with solderwick. This is more important with p.c.b.s which have not been air knifed and have small solder blobs at the pad corners. But for most projects this would only be recommended where a joint is to be mechanically or thermally stressed. A soldered switch anchor/contact or power device would need careful inspection.

The effect of a dilution in lead contamination is shown in Fig.6. A joint was repeatedly remade with TSC after a deliberate lead addition from some 60/40. The first blob on the left is dull and highly crystalline. The iron carries lead over to subsequent joints. But after four additions of TSC the surface becomes progressively brighter and stronger. Although a small grey spot persists, as total removal of lead is difficult and the TSC ternary will separate slightly under harsh conditions.

Fig.5. Lead contamination seen as a mottled surface.



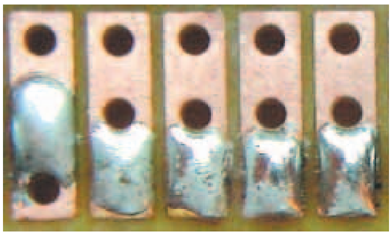


Fig.6. Effect of diminishing lead content.

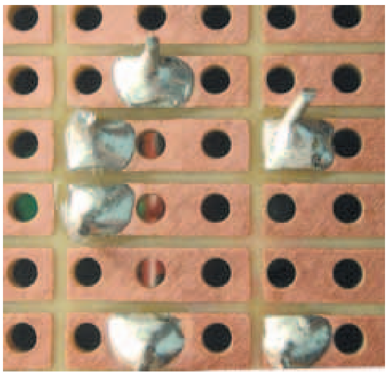


Fig.7. A completed circuit board using rosin based TSC with leaded components.

A slightly longer or shorter soldering time or a different temperature profile can lead to big changes in the structure of the contaminated joint. For small electronic projects, this may not be too serious, but where mechanical stress is present, particularly coupled with heat dissipation from power devices, reliability will be compromised. At the other end of the scale, the smaller joints used for surface mount devices are more likely to fall victim to contaminated spaces in the solder mass.

For 1206 and 0805 sized chips this is not so bad but a little care is suggested at the

The biggest present use of TSC solder will be for normal leaded components with their present lead-based finish. From the tests described above, the simplest approach is to use a rosin based TSC. To evaluate this, several new and clean leaded resistors and capacitors were selected. The result was some very adequate solder joints, as shown in Fig.7.

Close inspection shows some impurity and duller surfaces than we would expect from 60/40. On this scale the contaminated area is not a major portion of the joint and the circuit function should be satisfactory for signal level use. Of course, the component leads are still surrounded by a lead rich zone and experience will show how it would cope with heavy current.

TIP CLEANING

It is difficult to avoid frequent use of tip cleaners with lead-free solder for getting an iron tip back to working condition. The extended time at higher temperatures, coupled with more chemically reactive environment, can lead to rapid coating of the iron tip with a tough varnish-like organic film. This film can only be removed by the somewhat aggressive use of a tip cleaner like the familiar Multicore TTC product in a 15g tin.

The tip is then wiped clean with slightly moist rather than wet sponge, because water attacks the iron (Fe) coating. Any weakness in the iron coat will lead to ingress of tin-rich solder, which rapidly dissolves the copper core of the bit.

Once the tip is well cleaned and tinned, some TSC solder wire can be added and wiped off a couple of times to dilute the lead contamination from the tip cleaner. More aggressive, last resort, tip cleaners are based on copper or iron wool in a small container, or a home-made version using kitchen stainless steel scouring pad in a small bottle. Pushing the iron tip into this will readily defeat the tarnish and any debris falls to the bottom of the container.

IRON TEMPERATURE

By far the most popular soldering irons are unregulated. The heater, usually 12W or 25W, slowly feeds its energy into the copper mass of the bit, taking some 90 seconds to reach working temperature. When the tip is applied to the surface to be soldered, heat is dumped from the bit, aided by the excellent thermal conductivity of its copper core. The temperature of the work-piece and the solder rapidly rises to the solder melting point. At this point the human feedback system operates.

The flux rapidly flows across all surfaces, sweeping away surface dross and oxide layers. The solder flows, enveloped in a protective liquid flux coating, wetting all surfaces. The eye detects when this process is complete and the iron is removed. Although the tip is at about 350°C, the solder and the metals being joined only reach probably 220°C. Soldered joints must be made quickly, say under three seconds.

If the system stops working, due to poor wetting for example, the operator continues to apply heat and damage can occur, like de-lamination of tracks, overheating of components and so on. Another response is to add excessive solder to get more flux into the system. With higher melting TSC solder the heat capacity of the bit can be drained before the melting point is reached and the operator now relies on the slower rate of heat generated in the heater to pump up the temperature.

This extended time means that the heat has travelled further along the tracks and component leads. The flux will be decomposing and evaporating at this high temperature. Experience with TSC so far suggests that for small clean joints the same iron will suffice, but the extra pumping time needed to get 30°C higher is noticeable. For bigger joints and a snappier job a higher power iron may be considered, depending on what scale you are working.

Simpler temperature controlled irons can suffer from a time delay of several seconds between the demand signal for more heat and its delivery. This can still make soldering sluggish with the higher melting lead-free solder. More sophisticated control systems (e.g. JBC advanced stations) have a rapid recovery time of less than a second and are a pleasure to use.

REWORK

Dealing with the existing solder on a circuit under repair is likely to be problematic. There is no method available for easily determining the composition of solder used, although lead test papers similar to those used for paint testing may work. At this time the most obvious solution is to attempt the rework with TSC and plenty of flux. Professional repair workshops have reasonable access to product information. The surface mount industry is particularly advanced in rework technology with a wide range of advanced rework and inspection equipment available.

GO GREEN NOW

The changeover to lead-free is likely to take some time and we must get used to dealing with increasingly mixed technologies. Although our component stock, and indeed most devices purchased at present, are likely to be aimed at a lead-based industry, we can switch to lead-free solder now.

With a little care, good results are possible with lead-free TSC solder. We can continue circuit construction by using flux pens, good tip cleaning, and sensibly dealing with lead contamination. But like every other aspect of electronics, the art of soldering will get more complex and cannot be taken for granted. □

For information on conventional soldering techniques, read Alan Winstanley's well-acclaimed article on the subject, *Basic Soldering Guide*. This is available for free download via **www.epemag.wimborne.co.uk**, taking the Resources click-link from our home page.