Getting the Lead Out – Soldering with Lead-free Solders

This paper contains references to soldering copper, copper seams, or locks, etc. Revere Copper and Brass Incorporated (subsequently, Revere Copper Products, Inc.) conducted tests to determine the best practices for making seams in architectural copper applications. In addition to plain and coated coppers, seams were made with galvanized steel, Monel, stainless steel, and terne as base metals. While test results showed that not all metals solder with equal ease, or that joints of equal strength can be made in all metals, the principles of soldering are the same for these metals.

Definition of soldering

What is soldering, why is it of concern to roof consultants, and how does "lead-free" soldering differ from "conventional" soldering?

One on-line dictionary defines soldering as:

> *"A group of processes that join metals by heating them to a suitable temperature below the solidus of the base metals and applying a filler metal having a liquidus not exceeding 450°C (840°F). Molten filler metal is distributed between the closely fitted surfaces of the joint by capillary action."*

For students of history, in this definition "solidus" does not refer to the gold, Byzantine coin that weighed approximately 4.54 grams. Rather, it is "the highest temperature at which a material is completely solid," or the temperature at which a metal begins to melt.

"Liquidus" is "the lowest temperature at which a material is completely liquid." So, the definition of soft soldering may be reduced to:

> "a method of joining pieces of metal by applying another metal at or above its melting point."

Soft soldering (the process we are concerned with in architectural sheet metal work) is performed at temperatures below 450°C (842°F).

Hard soldering or brazing is similar to soft soldering except that the filler metal (solder) typically contains copper and melts at temperatures above 450°C (842°F). Very little brazing is done in architectural metal work.

Welding differs from soldering in that the base materials to be joined are melted during welding; they are not melted during soldering or brazing.

When locks in many sheet metals are properly engineered and soldered, the resulting seams can be as strong as the base metal. Further, soldered seams do not compromise the properties of the base metals.

History of soldering

Evidence exists tracing gold-based hard soldering back to 4000 BC. While interesting, this has nothing to do with the subject of lead-free soldering. Therefore, we jump ahead over 2,000 years to Northern Europe in 1900 BC.

Some of the earliest high-quality, soft soldering was done by the Celts and Gauls almost 4000 years ago. It is believed that the availability of tin-rich ore deposits lead to the discovery of soldering by the "Barbarians" before the Roman Empire. Quick to recognize a good thing, the Romans brought the techniques to the Eternal City. There, soldering was used extensively to join the lead sheets that lined the famous aqueducts.

The "keys" to good soldering have long been recognized and are fairly well understood:

- Clean metal
- Flux
- Joint design
- Good solder
- Heat source
- Technique

However, despite the fact that millions of soldered seams are made every day (most in electronics), the physics of soldering are not generally understood. Soldering involves complex interactions between materials including (but not limited to) phase change, reaction, product formation, dissolution (the process of going into solution), diffusion, fluid flow, and wetting (spread of liquid filler metal or flux).

Through the following discussion, graphs and video clips we will attempt to provide information that roof consultants need for a basic understanding of soldering architectural metals and the ability to recognize well-made soldered seams.

History of "lead-free" soldering

Historically, the most widely used solders were alloys of tin and lead. These alloys have been described as "remarkable." The combinations of these metals possess different properties than either metal by itself. Tin-lead solders have relatively low melting points; they can be used to join both high melting temperature metals (i.e., copper) and low-melting temperature metals (i.e., zinc); they do not oxidize rapidly when molten; have good strength and ductility; can withstand thermal cycling, and are resistant to corrosion, etc.

In its molten state, tin dissolves most architectural metals. During soldering, tin diffuses into the surface of the base metal creating a thin inter-metallic (alloy) transition between the base metal and the solder. (When copper is soldered, a Cu_6Sn_5 interface is created.)

Lead has limited solubility in most metals but combines readily with tin. In its molten state, lead reduces surface tension and assists in the flow of solder into a lock.

In some cases, a third or fourth metal is added to the tin-lead alloy for special properties.

The solder used most often for architectural sheet metal work is 50/50. (When referring to tin-lead solders, the first number is the percent tin content and the second number the percent lead. Thus, 60/40 solder contains 60% tin and 40% lead.)

Prior to enactment of the Safe Drinking Water Act Amendments (SDWA) of 1986, 50/50 solder was the most widely used medium for joining copper water tubes in potable water systems. The SDWA established the maximum contaminant level for lead in drinking water at 50 parts per billion. The SDWA also requires the use of "lead-free" pipes, fixtures, fitting, and solder in public water systems. Under the SDWA, lead-free means solder and fluxes cannot contain more than 0.2 percent lead. This effectively banned the use of tin-lead solders in water distribution systems.

As a sidebar, we would note that studies by EPA have shown that in most cases where conditions are such that lead pick-up can occur (soft, acidic waters that have low alkalinity), it generally tapers off after a new system is put into use. We would also note that lead pick-up can usually be avoided by treating such waters to make them non-aggressive. However, this is well beyond the scope of this paper.

More recently, the European Union and Japan enacted environmental legislation to sharply restrict (ban) the use of lead solders in electronics.

The European initiative – Restriction of Hazardous Substances (RoHS), also known as Lead-Free, restricts the use of six materials found in electrical and electronic products. The Japanese are directing their efforts in two areas. The "White Goods Recycling Act" calls for recycling or elimination of lead to reduce toxic materials being landfilled. At the same time, the Japanese electronics industry is doing all it can to comply with RoHS so as not to lose position in Europe.

Lead-bearing solders are still legal in the United States; however, there are indications that:

1. This may change, and
2. It may be wise to discontinue using or specifying lead and lead-based products for construction.

Specifically, "storm clouds" that are troubling to the building industry include:

- The OSHA fine of a Webster, New York, roofing and sheet metal contractor for lead exposure. As noted in the April 10, 2006, news release, the contractor was fined because it had not provided workers with safeguards (including monitoring of blood lead levels) during the demolition and replacement of a roof with a lead coating.
- Allegations that contamination of a pond at the Kane County (Illinois) Judicial Center was related to run-off from a roof. The county's suit to recover $4,000,000 in costs from the architect, contractor, and material supplier is on-going at this time.
- Efforts by the U.S. Department of Health to develop an "inter-agency task force (that) will investigate and promote strategies that reduce lead exposure from sources other than lead paint." (See Lead Poisoning Prevention Branch Updates, March 22, 2005.)

A prudent individual might conclude that it is only a matter of time before the use of lead-bearing solders in architecture will come under scrutiny. When that happens how long will it take before litigators initiate class-action suits against those who knew or should have known of the risks associated with such solders?

We are not suggesting that the above represent a real problem - only that history has a way of repeating itself when there is money to be made.

Soldering architectural sheet metals

Sheet metal shapes are often joined with soldered seams because it is quick and in-expensive when compared to other methods of making rigid seams, can be done at low temperatures, is easy (as will be discussed, "easy" is a relative term), and the seams are durable.

Soldered seams can be divided into two categories:

1. Those that hold pieces of metal together with little or no stress
2. Those that must be strong enough to transfer the stresses of expansion movement from one piece to another.

Examples of the first include locking strips soldered to roofing panels. Examples of the second are locked and soldered flat seams that join sections of gutter together. Revere does not endorse lapped and soldered seams for structural applications.

When the strength of seams must equal that of the base metal, Revere suggests 3/4-inch-wide locked and soldered seams for use with copper up to 20 ounces (0.027 inches) in thickness. For 24-ounce and heavier coppers, Revere suggests lapped, riveted, and soldered seams be used. In this case, the strength of the seam is supplied by the rivets and the solder provides waterproofing only.

Revere has tested 1/2-inch-wide locked and soldered seams. When these seams are made correctly and fully engaged, their strength can equal that of 16- and 20-ounce copper. However, if they are not fully engaged, these seams may not be strong enough to transfer expansion movement.

A 3/4-inch-seam allows more room for installer error and is therefore suggested. As previously noted, the "keys" to good soldering are:

- Clean metal
- Flux
- Joint design
- Good solder
- Heat source
- Technique

Clean metal

It is imperative that metal to receive solder be clean, dry, and free of oxides, dirt, oils, etc. Solder will not adhere to such foreign materials. Flux may clean some metals but laboratory tests clearly show that mechanical cleaning (i.e., sanding or polishing with emery paper) improves the strength of the seam. For this reason, Revere suggests heavy oxides be mechanically removed before fluxing. Mechanical cleaning offers the added benefit of providing "tooth" that contributes to solder adherence to the base metal.

Flux

Flux serves two purposes: a) removal of thin oxide films, and b) assistance in "drawing" the solder into the seam. (Fluxing is not a substitute for mechanically cleaning and is definitely necessary when soldering coated metals - i.e., FreedomGray™ tin-zinc, alloy-coated copper.)

Joint design

Solder is drawn through a locked seam by capillary action. The space between the pieces of metal to be joined must be sufficiently tight to ensure solder flows through the entire seam and joins all thicknesses of metal. If seams are malleted too tightly together, there may be insufficient solder to create an acceptable seam.

In all cases, tinning or pre-tinning the copper prior to forming the seam has been shown to result in significantly stronger seams than those that were not pre-tinned. Tinning can be done by flowing a thin coating of solder (same as will be used for the seam) or tin onto the metal with a soldering iron or by dipping the metal into a bath of molten solder/tin. In those applications where high joint strength is required, Revere suggests that bare (un-coated) architectural metals be pre-tinned before soldering.

Good solder

All solders are not created equal. Small amounts of impurities can influence the flow of solder in a seam, bonding to and with the base metals, seam strength, etc. As an example, the tensile strength and other properties of 50/50 solder can be adversely compromised if a small amount (less than 0.5%) of zinc, bismuth, or certain other metals is inadvertently introduced.

The best insurance the specifier has against the use of poor or inferior solders is to:

1. Require conformance with ASTM Standard Specification B32 or identify acceptable solder by manufacturer's name and identification.
2. Require that the installer provide manufacturer's certification for solder used.
3. Prohibit the use of solder bars "manufactured" by the contractor by mixing and melting short ends of bars to make more solder sticks.
4. Never alloy the mixing of tin-lead solders with lead-free solders.

Heat source

Heat used during soldering must be sufficient to raise the temperature of the entire seam to the point at which solder flows freely (above its melting point). Historically, coppers (irons) heated in charcoal or gas-fired pots or continuously heated coppers (torches) were used.

These methods are still the preferred/recommended heat source so long as sufficient heat is maintained throughout the soldering process.

However, under certain conditions, "direct flame" soldering may also be effective. Some mechanics may find direct-flame soldering faster and somewhat easier, particularly when using lead-free solders. Extreme caution, however, must be exercised to assure proper solder flow while avoiding over or spot heating and/or warping of the base metal and preventing combustion of the underlayment or substrate.

Technique

Previously, this author called soldering "easy," while noting that this is a relative term. In the author's experience, soldering is more art than science.

After 38 years of trying, I still cannot make good soldered seams. However, Anne Schade, a senior architectural products representative at Revere, made excellent seams the first time she picked up a soldering torch. Many mechanics with 20 or more years experience can solder no better than I. Soldering is one area where experience does not necessarily equate to skill.

The two mistakes seen most often are:

1. Time interval between cleaning, fluxing, and soldering.

   For proper adherence of solder, metals must be unoxidized and clean. Architectural metals oxidize rapidly. To effect good soldered seams, the base metal should be mechanically cleaned, fluxed, and soldered within a short period (four hours at the most) – not overnight or longer. If moisture and/or dirt get into a lock before it is soldered, it is doubtful that a good seam will be made.

2. Incorrect application of heat.

   In a well-made, locked, and soldered seam, the solder flows through the "S-turns" and joins all four thicknesses of metal. For this to occur, all four thicknesses of metal should be heated to 50° to 100°F above the liquidus temperature of the solder, at which point the solder will melt and begin to flow freely. When too little heat is applied or heat is applied only at the edge of the lock, it is unlikely that the metal will be heated sufficiently so that solder flows through the seam.

Lead-free soldering of architectural metals

Lead in tin-lead solders reduces surface tension and assists in flow of the solder into the lock. As a result, most mechanics find lead-free soldering more difficult, time consuming, and costly than soldering with tin/lead solders.

Why, then, should the building community turn away from a centuries-old, proven method of effecting strong, durable, weather-tight seams in sheet metals? The potential for increased regulatory control represents one reason; another, often overlooked reason is ultimate economics.

There are approximately 17-1/2 square feet of exposed solder per square of locked and soldered flat seam roofing that is made per "accepted industry standards." Does this amount of lead – particularly when combined with tin - represent a real or imagined concern? Each person who is responsible for the selection and specification of solder should remember that perception can easily become reality. Can a single species of mold really be responsible for all the adverse symptoms claimed (depression, rashes, nausea, hair loss, chronic fatigue syndrome, sexual dysfunction, etc.)? Do not ask the medical or scientific professions – ask any good litigator who advertises on television.

Assuming you do not want to learn the potential, ultimate cost of specifying the use of lead in construction the "hard way," what lead-free solders are available?

The most obvious solders are "pure tin" and 95/5 tin/antimony. Since 1986, the latter has become the standard solder for use in copper plumbing systems, primarily because of its relatively low cost compared to other "lead-free" solders. While there may be nothing wrong with these products from a technical standpoint, there are equally good and better choices for architectural sheet metal applications.

In late 2000, Revere contacted manufacturers of solder to determine the availability of lead-free products. Of the companies contacted, only Johnson Manufacturing of Princeton, Iowa, expressed interest in co-operating with Revere in an evaluation of lead-free solders for architectural applications.

After screening tests at Johnson's facility, Revere supplied several different solders, fluxes, and coppers (plain "red" and Freedom Gray) to three architectural sheet metal contractors. Under Revere's supervision, six experienced sheet metal mechanics made test specimens of 3/4-inch locked and soldered seams with the different solders and fluxes. Thirty-four specimens were made by soldering with "conventional" irons and three were made by "direct flame" soldering.

In keeping with similar tests conducted by the U.S. Department of Commerce, Bureau of Standards in 1930 and Revere Copper and Brass Incorporated in 1943, "no laboratory refinements were used. The quality of work was such as would be found on the best type of copper work."

However, unlike the samples that were used in the earlier tests, these samples were made by contractors from Vermont, Massachusetts, and Texas. This was done to eliminate the possibility of regional or personal bias or techniques affecting the results.

The 37 completed test specimens were sent to Ithaca Materials Research testing. Each specimen was cut into five one-inch wide samples for tensile testing. The breaking load (point of failure) in pounds along with the mode of failure were recorded. Failure modes were:

- Failed in seam – seam opened.
- Failed in "heat affected zone" – copper adjacent to the seam sheared.
- Failed in metal – copper away from the seam sheared.

In sixty-three percent of the samples made with lead-free solders, the base copper fractured (at or away from the seam) before the seam failed. Considering the variety of fluxes, heating techniques, and other variables employed in making the samples, this is very comparable to the 20 "benchmark" samples made with conventional tin-lead solders. (Eighty percent of these failed due to fracture of the base copper.)

Based on these tests and subsequent field observations, it is Revere's opinion that certain lead-free solders can be used in lieu of "conventional" 50/50 solder without loss of seam strength or durability.

Of the solders tested, the one that mechanics judged easiest to use also exhibited the best strength. This is a tin/antimony/copper/silver alloy marketed by Johnson as solder #497. The shear strength of #497 (5,294 psi) is greater than that of 63/37 solder (4,747 psi).

Of the fluxes evaluated, best results were obtained with a "tin-loaded" product – Johnson's E-127 Flux-'N-Solder with Pure Tin. This paste-type flux/solder is a blend of mild chlorides mixed with pure powdered tin. The powdered tin acts as a "magnet" and "draws" tin-rich solders into the lock. This helps compensate for the lack of flow normally associated with lead-free solders. The melting point of Johnson E-127 is 450°F. This is compatible with all common solders, including lead-free alloys.

Residues of E-127 are water-soluble. Nevertheless, as with any soldering flux, upon completion of soldering, all residues should be neutralized and removed by thoroughly washing with clean water. (Residues that are allowed to remain on the copper may cause long-term discoloration and uneven weathering.)

Failure of eighty percent of the samples made with #497 and E-127 flux occurred in the base copper strip before the seam failed (opened). As a result, we believe the properties of Johnson #497 are such that a competent mechanic can make seams that are stronger than 16- and 20-ounce copper.

The primary problem associated with lead-free solders relates to the solubility of copper in molten tin. This does not appear to affect the copper being soldered but does shorten the life of the soldering copper (iron). For this reason, some mechanics may consider using the "open flame" method of soldering (similar to soldering copper water tube) when using lead-free solders.

Although Revere prefers that soldering be done with properly heated coppers (irons) or continuously heated "torches," we are less concerned with the heat source than we are the quality of the finished seam. The only caveat being that whenever sheet metals are soldered with an open flame, extreme caution must be exercised to prevent warping of the base metal plus combustion of the underlayment and/or structural deck below the copper.

We would also note that when any soldering is undertaken, the contractor must read and follow all manufacturers' instructions, guidelines, MSDS sheets, etc.

Quality control of soldered seams

Perhaps the best way to ensure well-made, lead-free soldered seams is to pre-qualify all mechanics who will be soldering. Pre-qualification need not be complicated but it should involve soldering full-size test pieces that are subjected to the same conditions as will be encountered on the project. If the project involves vertical soldered seams, similar seams should be part of the test; if field conditions require soldering in cramped or close quarters, the test should include these conditions.

Upon completion of soldering, the test specimen should be cut into strips approximately one-inch wide so that the seam can be inspected for solder flow.

In a well-made, locked, and soldered seam, the solder will flow through the "S-turns" and join all four thicknesses of metal. This does not mean that the solder will be smooth and complete with no "voids" or "inclusions." In fact, when soldered seams are sectioned, it is not at all uncommon to find evidence of small "bubbles" or "tubes" - particularly at an "S-turn." These do not affect the strength or durability of the seam and are no reason for rejection.

Following visual inspection, the strips can be (or at least can be attempted to be) "pulled to failure" by hand. (One end of the strip is secured in a vice and the other end pulled with Vice-Grips®.) This is to inspect the mode of failure - not determine the strength achieved. Failure (if it can be achieved) should be cohesive (shearing within the solder); the solder should not be completely pulled off the base metal (adhesive failure).

The easiest "on-site" method of ensuring quality is visual inspection of finished seams.

The appearance of a soldered seam can often be an indication of its strength and how well it was made. Seams that are made with a soldering copper or continuously heated torch should have a "track of solder" on top of the seam. This is an indication that the soldering copper was placed on the seam, thus heating (hopefully) all thicknesses of metal.

If there is little or no solder on top of the seam but an accumulation adjacent to it (especially if the adjacent solder looks as though it was thrown there), it is often a sign of an improperly made seam. When such a seam is sectioned, it is usually found that the solder penetrated only to the first "S-turn." In effect, the seam is little more than a simple lapped and soldered seam.

If necessary or required by specification, samples of finished seams can be cut and inspected as described above. If the seams are to be tensile tested (pulled to failure), field samples should be at least three inches wide and have four inches of base metal on either side of the seam. Laboratory test pieces – typically one-inch wide – can be cut from these samples without inadvertently compromising the seam.

Unfortunately, there is no good way to repair a poorly made or broken soldered seam. The only way to correct the condition and ensure a strong durable seam is to open (un-solder) the seam, thoroughly clean the base metal, then re-form and re-solder the seam in the correct manner.

Conclusion

It must be noted that all metals do not solder with equal ease, develop the same seam strengths, and/or can use (require) the same fluxes, solders, and heating techniques as copper. What works with copper may not work with another metal. Always check with the manufacturer of the metal being soldered - as well as the manufacturer of the flux and solder - before initiating work with new products.