The Pathology of the Soldered Joint

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Over the last few decades, soldering has graduated from an art, based mainly on tradition and know-how, to a technology backed by research and quantitative exploration of its underlying physics and chemistry. At the same time, the economic importance of soldering has grown significantly.

The number of joints, made daily in industry in the UK is counted in 10^7. The soldering stage in the manufacturing sequence of a given product provides an important contribution to the total added value of the assembly. Bad soldering on the other hand is expensive. For instance, to correct a badly made joint on a printed circuit board costs at least ten times as much as the original, automatically made joint.

Percentage of joints needing correction	Cost of resoldering 100 joints
0.1%	£ 0.50
5%	£ 1.75

(1)

Thus, it is important to avoid making joints which are faulty, or which develop faults in service. The field of enquiry which deals with defective joints, their causes, diagnosis, cure, and prevention, might well be called "The Pathology of the Soldered Joint",

I Faults due to constructional factors

These could be called "congenital defects". The first question to be asked here is :

Was soldering the correct method of joining ?

A soldered joint has three legitimate functions :

Conduction of electricity
Conduction of heat
Forming a liquid—or gas-tight seal

In fact, these three functions relate to the three main industrial uses of solder, electronic industry, the car-radiator industry and can-making.

Using a soft soldered joint for purposes other than the above 3 is likely to lead to trouble, though there are some admissible sub-functions of soldered joints, such as securing two components against relative movement, as long as the loads to be sustained by the joint do not exceed approx. 1 kp/mm² in shear or 0.5 kp/mm² in tension. A design which uses a soft soldered joint to transmit loads or forces above these limits is dangerous.

Thermal demands on soldered joints must be limited as well : At 100°C, a joint made with Pb/Sn solder will have lost half its room-temperature strength. On no account should it be exposed for long to temperatures above 150°C. Similarly, joints made with normal solders become dangerously brittle below 30°C.

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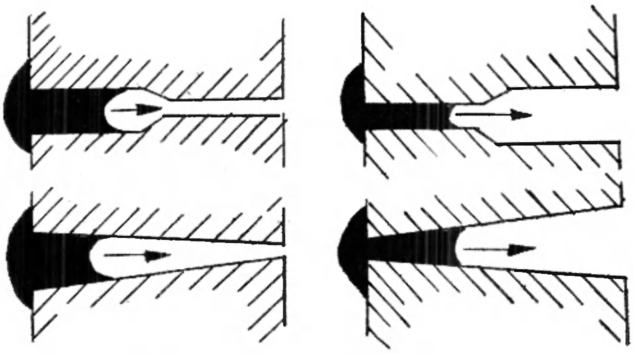
Assuming, soldering was the correct joining method to use, the next question is

Is the design such that, even with the correct soldering materials and equipment, it is improbable or impossible to make a good joint ?

Was it possible to heat the parts to the correct soldering temperature ? Or was the assembly too heavy or inaccessible to be heated, at least economically ? A famous example is the nameplate, which the design called to be soldered to a 1 ton flywheel.

Next, was the *Joint geometry* such that capillary forces could induce the solder to fill the joint ? A joint gap should be either parallel, or taper away from the joint entrance, not become wider. Furthermore, is there an escape route for the air, the flux, and the fluxvapours which the molten solder is expected to displace ? Finally was the molten solder expected to fill capillary joints of large area, which imply the danger of air, flux or gas being overtaken by the molten solder, which flows more quickly along the edge than in the middle, thus trapping the residues in a central void ? (Figs. 1 and 2)

In certain circumstances, the molten solder may have a *destructive effect on the substrate.* Austenitic steels are prone to intergranular penetration by molten solder in the presence of imposed or residual stresses. Similar rapid and sometimes catastrophic penetration can occur during the soft soldering of aluminium cable sheaths.



Correct Wrong

Fig. 1. Joins taper

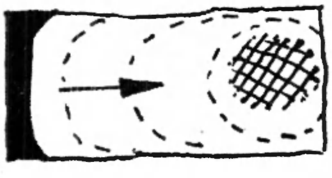


Fig. 2. Advancing Solder front trapping flux residue

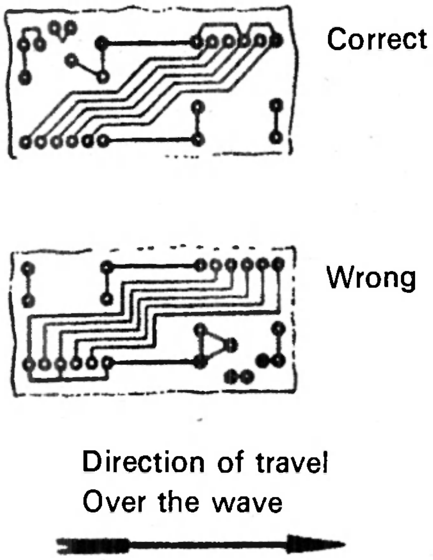


Fig. 3. Conductor patterns for wave soldering

With printed circuits, certain conductor configurations are prone to lead to untidy joints or to bridging, which will be rejected by quality control and lead to expensive re-soldering. (Fig. 3)

II The badly soldered joint

A correctly designed joint may of course be badly soldered, because one or more of the parameters of the soldering process were wrong. Soldering defects arising under this heading may be called "accidents at birth".

Too low a soldering temperature, or too steep a temperature gradient away from the heatsource may prevent the ready flow of the molten solder, or even its alloying with the substrate.

Too high a soldering temperature may cause weak joints through the formation of excessively thick intermetallic layers, or by degrading the flux, making it ineffective, or too viscous to move aside and make room for the advancing solder. A specific example is the presence of sparingly soluble zinc-oxychloride flux residue, which causes and at the same time masks leaky seams in car radiators, soldered with zinc chloride flux. Such leaks escape detection in the testing tank and become apparent only after a certain period of service.

Contaminated solder may be unable to perform properly. Contaminants like Zn, Cd, and Al form oxide skins on the molten solder, which impede its flow, even in the presence of strong fluxes. Fe, Ni, and Cu in amounts above their temperature—and tin-content

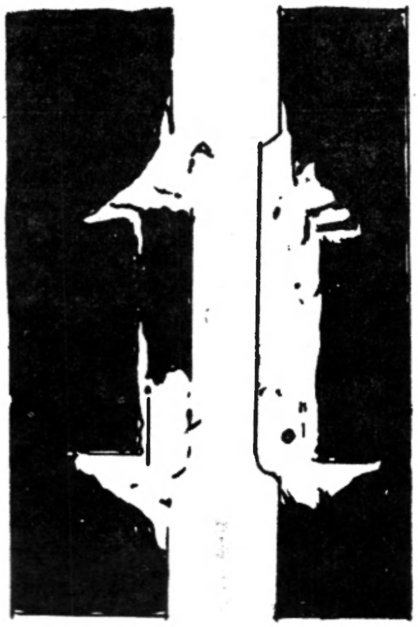


Fig. 4. Cavity in plated-through hole.

dependent solubility limits in molten solder form small primary crystals in the melt which increase its viscosity, impede its flow, and spoil the appearance of the joint.

Circumstances can arise, for instance with through-plated holes in printed circuit boards, where *trapped vapours* from residual processing liquors push the solder out of an already filled joint and cause cavities or open joints. (Fig. 4).

The presence of *contaminating layers on the substrate* of a nature or in amounts which are beyond the scavenging capacity of the flux may prevent wetting (i.e. the solder cannot get to where it is needed) or dewetting (i.e. the solder does not stay where it has been put).

Sometimes such layers are hidden underneath galvanic coatings which have been applied to enhance or preserve the solderability of a given substrate, because cleaning prior to plating was inadequate. If such layers are soluble in molten solder (e.g. Au or Sn/Pb), unsolderable substrate will be exposed, once the galvanic coating has disappeared during soldering.

III Damage caused after soldering

Defects under this heading might be called "post-natal accidents". A frequent cause of cracked joints is a relative movement of the joint members while the solder sets, or before it has cooled sufficiently to form a strong bond. Such relative movement may be caused by simple lack of skill, or bad soldering practice : Inadequate jigging, rapid chilling or even quenching of the assembly after soldering, or handling it while it is still too hot. Badly designed soldering jigs, which constrain expansion during soldering and thus cause movement during cooling, are another cause of solidification cracks. Certain solders, such as leadbase solders with low tin contents, or leadfree tin-antimony solders, which cannot tolerate even minute Pb contamination, are prone to hot-shortness, which can cause hairline cracks in soldered joints during solidification. Large, heavy assemblies are particularly prone to this kind of trouble.

The trimming of leadwires on soldered printed circuit boards is another post-natal risk. Handcropping with blunt tools may literally tear the wire out of the joint. With machine trimming or cutting, a second soldering operation is often carried out after the trimming, to repair the damage caused by the cutters.

IV The overstressed joint

A welding engineer can consult a whole library of data, relating to permissible loads for welded joints of any conceivable configuration, in any material that is at all weldable. The data available to a designer of soldered joints can easily be accommodated on a single page, and most of them are tentative and cautious. This is not the place to discuss this difference between the two technologies and the reasons for it. But in any case, the designer must bear in mind, that soldered joints are mechanically weak, in most cases weaker than the joint members.

There is a virtue in this : A soldered joint can flow plastically and thus absorb strains or deformations in the assembly, which would destroy a less yielding joint. This type of stressing, in many cases a repeated, alternating one, is often caused by thermal cycling of the assembly. Overstressing of a joint can be caused either by unsuitable design, or by an unavoidable mismatch between the thermal expansion of the joint members. An example is the relative movement between leadwire and copper-laminate in printed circuit boards during thermal cycling. (2).

Expansion Mismatch between Leadwires and Board, (1.6 mm thick)

Temperature Interval	Copper Wire	Kovar Wire
-20 to +80°C	1 micron	2 microns
-40 to +90°C	3 microns	5 microns

The behaviour of soldered joints under such conditions is of great practical importance, and a number of design rules have been established, especially for assemblies exposed to aerospatial environments, to make joints capable to cope with these stresses. The test parameters used by various workers in this field vary widely, and direct comparison of their results is therefore difficult. Under severe thermal cycling (−40 to+150°C) most solders show severe metallurgical damage after 3000 cycles. (3).

From both practical experience and published work, a few rules emerge : Solders containing Sb are less resistant to thermal cycling, while the presence of small amounts of Ag is helpful. For extreme thermal cycling, solders with a single-phase metallographical structure (such as low-tin leadbase solders, which also have the advantage of a higher solidus temperature) are best.

Apart from cracking through thermal stressing, joints can be damaged through an excessive growth of the inter-metallic layer between solder and substrate, which proceeds through diffusion in the solid state. Another failure through thermal overstress can be observed in commutators of high-duty electric motors, where under high loads/high temperatures the solder may be thrown by centrifugal force from the joints.

Yet another overstress is of a chemical nature : Soldered joints are highly heterogeneous structures, and in the presence of an electrolyte, they are, at least in theory, prone to electrolytic corrosion. Cooling systems and plumbing installations are practical examples of such situations. Measures to avoid such corrosion are well understood on the whole, but with the soft soldering of aluminium, the EMF between solder, intermetallic layer and substrate is of such magnitude, that it is often advisable to use a joining method other than soldering where the joint is likely to become moist.

V Inspection

Inspection may be likened to medical examination and diagnosis. In some industries, diagnostic methods yield objective and unequivocal results : In a radiator factory, soldered units are connected with a compressed-air line and immersed in water. Leaks show up as air bubbles. In can-making, leaks are detected during processing after filling.

With electronic assemblies, identification of faulty joints is more subjective : Joint appearance is almost the only available criterion of quality. It is a very reliable criterion, but joint-quality control, if it is to remain rational and not to become expensively overzealous or dangerously liberal, demands definitive, recognisable, and repeatable standards. The International Tin Research Institute has rendered an invaluable service to the electronic industry by providing such standards.

Inspection, which is often coupled with corrective soldering (de-soldering and re-soldering), is one of the responsible (and potentially cost-creating) operations in the soldering sequence.

VI De-Soldering and Re-Soldering

These operations could be called remedial treatment, and like all medical attention, they are expensive. The removal of defective or incorrectly inserted components involves de-soldering. The aim of desoldering is to restore the status quo, which existed before the offending component was soldered into place. Thus, not only do the leadwires have to be removed from the holes, but the solder as well. The solder has to be melted first, then emptied from the joint, and the component lead-wire is extracted from the hole at the same time, or immediately afterwards. The lands and the hole must be left free from solder, and as solderable as they were in the first place.

With most desoldering methods, the solder is melted with a soldering iron, often specially shaped, but small soldering baths or miniature solder-waves, which fit the joint area are also used. The molten solder is removed either with a pretinned copperbraid, which acts like a piece of blotting paper, or it is sucked from the joint through a bore in the soldering tip or through a separate nozzle and collected in a receptacle. Blowing the solder from the joint is to be discouraged for environmental reasons. Safe and efficient desoldering poses problems with multilayer boards where the temperature gradient along a plated through hole makes it difficult to get the solder hot enough at the far end without overheating the board at the other one. With multilead components, desoldering calls for the simultaneous extraction of all the leads, and this too can have its problems. Development of desoldering equipment really suitable for these tasks continues.

A main problem with desoldering is not to cause more damage rather than repairing existing faults, by disrupting conductor paths inside or adjacent to the hole, or by damaging the bond between copper laminate and substrate. Desoldering and corrective soldering is a highly skilled manual job, comparable to micro-surgery, which requires training, judgment, first-class equipment, and certainly also some appreciation of the cost factor.

VII Fault Prevention

Fault prevention, like preventive medicine, seeks to remove the cause of these faults. In soldering, most of them can be traced back to some human factor and it is here where prevention must start.

To begin with, the designer needs data and guidelines. Most of what matters here is known and understood, and the problem is one of communication and education.

Solderability problems probably still call for continuing basic research, which has already elucidated many previously baffling problems. Further data in this field will be of great help to designers and material-selection engineers.

Training soldering personnel and production engineers is a continuing task, which falls on colleges, trade- and craft-associations and on industry itself alike. Quality control finally, as has already been said, calls for a singularly high standard of training and responsibility.

To return to the starting point : Soldering may no longer be a secret art. But it still demands skill and understanding. Both can and must be taught and communicated.

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