A Metallurgical Approach to Cracked Solder Joints

Observations made on the structure of failed joints lead to some useful conclusions but also indicate the need for more research

BY D. T. NOVICK

Introduction

In the past five years, considerable attention has been given to the technologically important problem of cracked solder joints occurring in printed wiring boards. A review of the papers and reports now available leads to the observation that most work deals with effects of gold,[1–8] thermal cycling[9–19] and conformal coating,[9,12 16–18] Studies of gold in solder joints generally deal with the effect on mechanical properties, usually in bulk solder, and the appearance of highly embrittling interface intermetallics. Investigations of thermal cycling and conformal coating usually run hand in hand but have been directed more towards producing a mechanical failure model than looking into the effects of process irregularities and metallurgical structure in promoting ultimate fracture.

Approaches to joint repair or crack prevention generally involve structural modification to strengthen the joint and remove thermally induced stresses rather than modification of the metallurgical structure or prevention of process induced irregularities that act as stress risers or crack nuclei.

As a result, there have been periodic recurrences of fatigue failure in spite of design modification. One exception to this approach has been in the consideration of gold/tin intermetallics. Here, studies pointing out the deleterious effects have recommended metallurgically corrective approaches based on elimination or careful control of gold deposits in areas to be soldered.

Curiously, all failure models involve consideration of shear, creep, ultimate tensile strength and a host of other bulk solder mechanical strength properties. Nowhere is there evidence of an investigation of fracture mechanics, fracture being the mode of ultimate failure. This in spite of the fact that its importance is well established.[9] Likewise, repair and prevention of cracked solder joints, except where gold is present, is never performed with an eye to fatigue failure by crack propagation through the presence of singularities representing crack nuclei. It is hoped that this presentation will begin to remove this gross oversight.

D. T. NOVICK is Corporate Staff Metallurgist and Industrial Consultant, Alpha Metals, Inc. *Paper presented at the AWS First International Soldering Conference held at the AWS Annual Meeting in Detroit, April 10-14, 1972.*

Fracture

The most difficult factor to deal with in studying fracture of solder joints in printed wiring boards is that it is almost totally impossible to nondestructively observe the fracture surface. Except for the case of a lead which has been completely pulled from the printed wiring board, a cracked joint must be mounted and crossectioned for observation. Since this either destroys source data or fails to reach it, a great amount of experience and patience is necessary before meaningful results may be obtained and even then, the evidence can be, at best, only circumstantial. Nevertheless, because a laboratory is not a court of law, it is possible to draw many conclusions based on these observations. Before one can begin, it is necessary to have some knowledge of the different types of fracture. If one considers the processes occurring, fracture can be classified into five basic types — ductile, brittle, adiabatic shear, creep and fatigue.[20] A definitive study of these fracture modes may be found in the text referenced.

Ductile Fracture

Ductile fracture usually occurs in three distinct stages under tensile stress, although compression or torsion (shear) can also cause failure. As the material plastically deforms and "necking" begins, cavities are created in the necked region. These cavities coalesce into a void, crack nucleus, which becomes large enough to propagate transversely to the applied stress. At this point, the crack nucleus becomes a full fledged crack and spreads to the surface, plastically, at 45 deg to the tensile axis. The result is the typical "cup and cone" fracture of ductile failure. Laboratory observation indicates that when bulk solder specimens fail in tension, or torsion, they exhibit typical "cup and cone" fracture.[21] In finer configuration, using scanning electron microscopy, ductile fractures feature a "dimpled" surface geometry. This, too, has been observed on fractured solder surfaces.[22]

Brittle Fracture

The basic difference between brittle and ductile fracture is that plastic deformation is not essential to crack extension in brittle fracture, though it may occur. Brittle fracture nearly always occurs crystallographically. Crack nuclei for brittle failure need to be longer than those for ductile failure and may be initiated by slip or twinning associated with yeilding. Initial cracking by ductile failure can also produce large cracks that transform into brittle cracks. Here, it is also necessary that very little plastic deformation occurs. Furthermore, the yield stress must be strain rate sensitive so that a crack can pass through an area before slip occurs.

Of interesting note is the fact that tin-lead alloys are super-plastic, i.e., highly strain rate sensitive, such that yield stress may be greatly increased as strain rate increases. This implies that at low strain rates, the material should fail in a ductile manner while at high strain rates, the material may begin to fail in a brittle manner given proper combinations of conditions. Tin is known to fail in a brittle manner as are many intermetallic compounds.

Adiabatic Shear

Fracture in adiabatic shear appears to be due to high speed deformation effects which do not occur in any of the processes we are concerned with in printed wiring boards. As such, this type of fracture will not be discussed.

Creep

Creep is the process of continuous deformation under a static load greater than the yield stress. Three types of creep occur in metals; logarithmic, recovery and diffusional. Since the metals and alloys we are concerned with are technologically used at temperatures in which recovery and possibly diffusional creep can be found, logarithmic creep will not be discussed. (Normal room temperature conditions of tin and most tin-lead alloys place them in the range $T > 0.6\ T_{mp}$ or in the "hot working" range.) The specific processes of recovery and diffusional creep are too detailed to take up here. Suffice it to say that during normal deformation, crystallographic slip and cross slip can occur until forces opposing further deformation build up. During recovery and diffusional creep, these forces dissipate by the recovery mechanism of recrystallization or polygonization. Further deformation occurs by a rejuvenation of the driving mechanism.

To further complicate this, grain and phase boundaries become glissile, i.e., become fluid and can move. These slide until some natural obstacle blocks further advance of deformation. At this point, the recovery process acts to free the blockage. As a result, voids are created which ultimately grow in volume to a size that can support crack propagation. Under these conditions, fracture occurs.

Tin is known to polygonize and lead recrystallizes under conditions supporting creep. Both lead and tin undergo grain boundary sliding. As with many other metals, the introduction of solute elements and dispersed phases can "harden" tin and lead against easy creep. Tin and lead, however, as well as their alloys, fail rapidly in creep under conditions of constant load because the recovery mechanisms can work rapidly to restore easy flow conditions.

Fatigue

Fatigue is that process whereby a metal fails during the application of a stress less than the usual fracture stress. This stress must be applied numerous times before failure can occur. The metallurgical symptom of fatigue is the presence of slip bands or microcracks. These microcracks usually originate at the surface and may occur as the result of some surface defect or of slip-produced protrusions and extrusions on the metal surface.

Superimposed stresses appear to affect the system in the direction that stress would normally react to a crack, i.e., tension would speed up failure and compression slow it down. Since plastic strain occurs during fatigue cycling, strain hardening effects appear. The most difficult problem encountered with fatigue is that the damage caused by cyclic stressing appears in microscopically small areas, often defying recognition or identification.

Fatigue failure generally begins as a result of transcrystalline failure at the surface. These cracks propagate along slip bands. As a result propagation of fatigue has the same general features as slip propagation and can be held up by the same mechanisms that hinder slip.

In addition to this type of fatigue crack, fissures can occur along grain boundaries or internal surfaces. These cracks are characterized in the same manner as creep induced cracks, i.e., by the production of grain boundary cavities. Lead is known to fail in fatigue at room temperature by intergranular or grain boundary fracture. Tin twins in fatigue at room temperature, a process also producing internal cavities.

Structural Model

Obviously, if one wanted to be a strict purist, his approach to a new problem would be to introduce variables into an ideally perfect model. Since production does not normally deal with ideal situations, it would be naive to use a perfect model for an evaluation of a real situation. This paper assumes then, the existence of a real model or models, namely, three solder joint configurations:

Type I — Single-sided printed wiring board

Type II — Double-sided printed wiring board with no plated-through hole

Type III — Double-sided printed wiring board with plated-through hole

Multilayer boards will be neglected as such, but for the purpose of those interested, can be treated as a special case of Type III configuration.

It would be very simple to stop at this point and attempt to treat the configuration mechanically as an isotropic two dimensional material, determining stress distributions occurring under a wide variety of probable real conditions.

The difficulty is, that while this approach should be taken as a first step, it is still too basic to be of any more than academic interest here. Some work has already been performed,[9,16-19] It seems, however, that the most expedient approach at this point would be one which ignores the theoretical mathematical consideration and looks into the observable facts. Doing this, it will become possible to see what is inferred by observation in the hope of arriving at some hypothesis by which one can build a workable approach to solder interconnects.

The metallurgical structure of a solder joint in a printed wiring board is complex, built of the copper on the wiring board, the solder and the component lead wire which can be copper, nickel, iron or combinations thereof. To make matters worse, boards and component leads may be plated with tin, solder, nickel or gold and occasionally cadmium or silver, or they may be hot dipped in tin or solder. While usually composed of 60 tin/40 lead or 63 tin/37 lead, solders can be of a wide variety of materials sometimes including silver, indium, bismuth, cadmium and antimony in addition to tin and lead. Many solders have a eutectic structure, but many also contain dendritic structures of solid solutions or dispersed intermetallic compounds. On some occasions, the solder may be a solid solution with finely dispersed intermetallic phases. This latter case, however, is not frequently met.

Crack Sources in Solder Joints

The previous discussion has indicated that failure by any mode of fracture requires the existence of a microcrack or fissure. Since cracked solder joints concern fracture failure of solder joints, it seems obvious that a natural approach would be to look at whole and cracked solder joints for some evidence of these crack nuclei. Having observed hundreds of such configurations, Novick and Long[23] proposed the following possibilities:

- A. Process Induced
  - 1. Poor wetting
  - 2. Poor design
- B. Constitutionally Induced
  - 1. Component Phases
    - a) Major constituents
    - b) Minor constituents
  - 2. Impurities
    - a) Solder impurities
    - b) Process impurities
- C. Mechanically Induced
  - 1. Fatigue
    - a) Thermal
    - b) Vibrational
  - 2. Thermal Shock
  - 3. Constant Load

With list in hand, it now becomes the job of the laboratory to determine how accurate these predictions were. Since some of the information leading to the source listing was not intuitive but direct observation, it was not essential that all areas be investigated. Verification was considered to be important where limited or questionable identification was involved. At all times it must be remembered that finding microcracks is like looking for a needle in a haystack. Observations are equally of failed and unfailed joints.

Process Induced Microcracks

It appears, from the investigation of many cracked solder joints, that a generalization can be made that most failures are the result of process induced flaws or singularities. This author would guess that at least 75% of all problems arise from poor wetting or poor design.

Figures 1 and 2 show examples of cracks appearing in Type I and Type III solder joints. The failure of Type I joint (Fig. 1) is a crack emanating from the edge of the copper conductor pad. No wetting has taken place at this interior surface. Likewise, the crack following the component lead in the Type III solder joint (Fig. 2) shows points along the lead devoid of solder. With no matching interfacial intermetallic compound in the solder to indicate fracture at the component-intermetallic face following wetting, it must be concluded that wetting had not taken place. Under the particular mechanical conditions applied to this joint, the voids created by the nonwetting conditions act as crack nuclei. It is evident that anything preventing good solderability of the surfaces to be joined is a potential contributor to cracked solder joints.

The second source of microcracks from processing is poor design.

Fig. 1—Type I joint showing failure due to nonwetted surface. (a) Unwetted surface; (b) fatigue protrusion

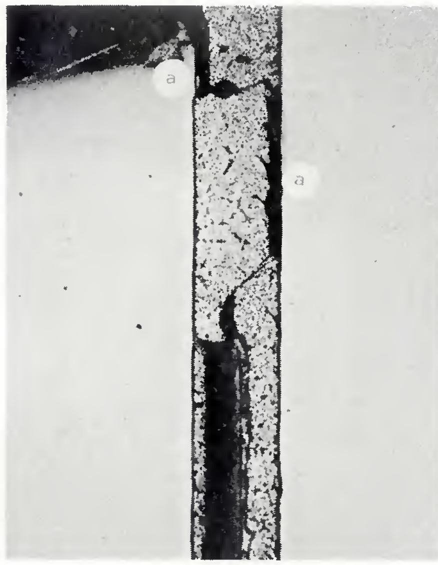

Fig. 2—Failure in Type III joint due to nonwetted surfaces shown at (a)

Loosely included is poor process technique. Among the offenders is the use of the Type I joints when heavy stressing is to be anticipated, and Type II joints with their lack of internal anchorage and their built in voids.

Poor design features include (1) too little clearance of components on top of the boards so that gases from fluxing action cannot escape becoming entrapped within the joint (usually in Type III joints); (2) improper curing of the printed wiring board causing outgasing of the vapors in the board during soldering; (3) improper drilling of holes leaving burrs on the copper or debris in the through holes; (4) improper plating of copper in the through holes of Type III joints; (5) improper cleaning of plating residues causing the implantation of corrosive residues that are not compatible with the surrounding metal.

While it is not possible to delineate all of the evidence pointing to the above conclusions, sufficient incriminating data is available with regard to each condition. Among available data, Fig. 3 shows a crack in a Type I solder joint. This type of crack can occur in all three types of joint but is used here to illustrate the result of poor design and heavy stressing. The crack is seen to propagate through a very coarse or "divorced" eutectic structure. It must be remembered that most solders are normally at "hot" working temperature at ambient conditions so that it would not be unusual to have a large amount of diffusional rearrangement of material in areas that were highly stressed.

The initial growth of the divorced eutectic zone might at first provide adequate recovery for the strained

Fig. 3—Crack due to poor structural design, resulting in insufficient support under load. (a) Fatigue induced eutectic coarsening (divorced eutectic); (b) fatigue protrusion

system but, as a result of one or another of the mechanisms previously discussed, a microcrack formed to act as a crack nuclei, ultimately propagating to failure. What is important here is to note that the applied stress was sufficient to cause a total reorientation of the normal eutectic structure. Obviously, the Type I joint design was, in this case, inadequate to carry the applied load.

Figure 4 shows a cracked Type I joint with a trapped void associated with the crack. It is impossible to state unequivocally that voids cause cracks or what this particular void was

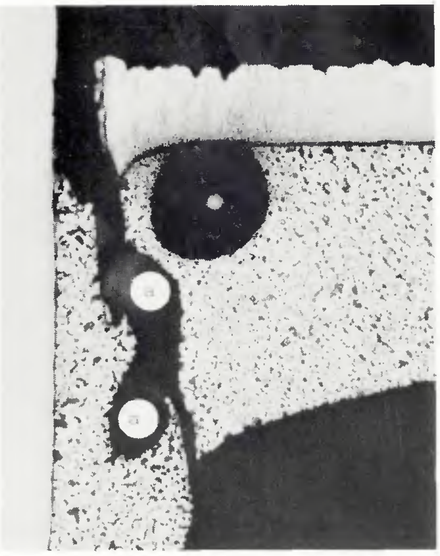

Fig. 4—Crack associated with trapped void show at (a)

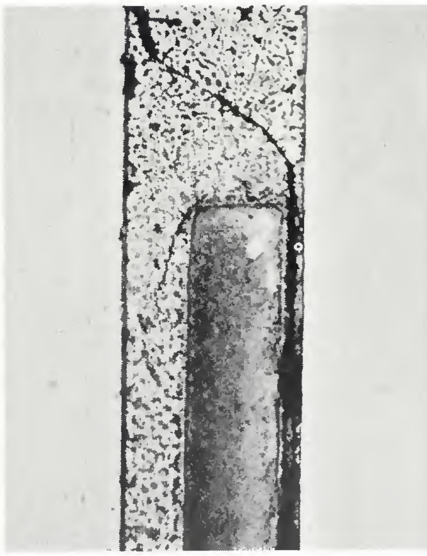

Fig. 5—Fracture through lead-rich solder constituent. (Light phase, tin-rich; dark phase, lead-rich)

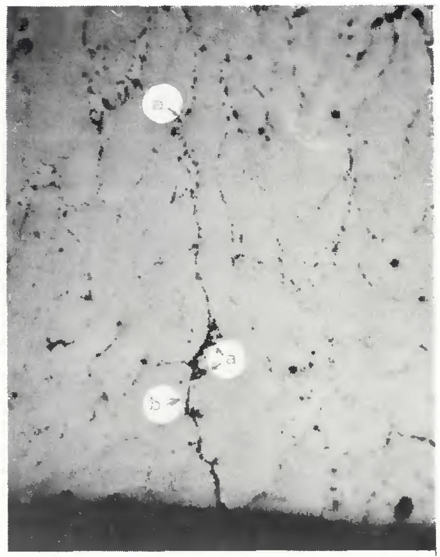

Fig. 6—Minor constituent segregation induced cracking. (a) Constituent particle precipitation in grain boundary; (b) cracked grain boundary.

caused by. Experience teaches that most often the problem is trapped flux or vapors from the boards. Voids from water vapor exuding from boards often have associated breaks or fissures in the through hole copper. While there is no hard data proving that voids such as this cause cracks, a very large percentage of cracks have associated voids in the solder, along unwetted surfaces, or along the length of the crack. It is hard to tell whether a void or an irregularity on the void surface acts as a stress raiser of sufficient influence to cause a crack to nucleate and propagate or if cracks propagate between voids due to the breaks in the continuity of the solder. In either case, it is obvious that the presence of voids is undesirable.

Broken and shattered through hole copper is often found as floating debris in failed solder joints, especially in voids. Improperly processed boards outgas at pressures high enough to cause the copper to fissure or blow out into the molten solder. The lack of through hole support and the presence of the copper in the solder void if attached to the surface can lead to inherent weaknesses or instability under load, culminating in low stress fracture.

The 1968 report on solder joint reliability presented to NASA by Westinghouse[9] indicated that when solder joints were soundly made, cracking occurred through the bulk solder itself. It appeared to Westinghouse's investigators that cracking along the solder-lead interface prevailed only when component lead wires were improperly prepared, i.e., unsolderable and is in agreement with the facts just discussed. Chadwick[24] has reported similar observations.

Constitutionally Induced Microcracks

The distinction between microcracks resulting from the constituents of an alloy and applied mechanical stresses is very diffuclt to make. Certainly, the argument can be made that the defect creating a crack nuclei could never exist if certain major, minor or impurity constituents of an alloy did not exist or were not used in combination. An argument can also be centered about the point that if mechanical conditions were properly controlled, the mere existences of a defect would not mean that a crack nuclei would form. The total argument then develops into that age old question. What came first, the chicken or the egg? Rather than attempt to enter a philosophical discussion, this and the next section of the paper will deal separately with crack sources due to each variable and will be concerned only with speculation about how they are interdependent.

Figure 5 depicts a typical fracture within soldered interconnects. It is interesting to note that the fracture path follows the lead-rich portion of the eutectic structure. This observation has been made elsewhere[25,26] so that data supporting the concept of major component contribution to failure is well documented. There is no hypothesis today with regard to this observation.

Figure 6 is a photomicrograph of a high tin bearing solder and does not contain a eutectic structure. This solder normally crystallizes as tin solid solution. Here, the figure indicates that the cooling conditions were such that several of the minor constituents precipitated out of solution within the grain boundary regions causing these areas to become highly embrittled. As easily seen, the resultant structure was an easy path for fracture, and there is a strong probability that during stress, grain boundary sliding caused shattering of the precipitates. This shattered material, as well as the voids created by precipitate drag, lead to the crack nuclei to promote failure. Wild[27] has made similar segregation observations.

Figures 7 and 8 show the effects of impurity pickup. In Figure 7 solder has reacted extensively with most of the gold present as a protective layer over an iron-nickel alloy lead. The resultant impurity-induced secondary phase deposited at the interface is brittle, and, under stress, has shattered, leaving small fissures and voids which act as the microcracks for failure propagation. Had this material been completely dissolved into the molten solder, it might have resulted in a widely dispersed phase adding to joint strength by a precipitation hardening mechanism. This, too, if overaged, could shatter under stress and lead to ultimate creep or fatigue failure.

Figure 8 is an example of this latter impurity effect. Here, too, high heat and too long soldering time has caused extensive dissolution of the base metal being soldered. Gross precipitation of the impurity intermetallic has lead to easy cracking under operational stresses. The material cannot support cyclical mechanical stress, shattering and leaving fissures which can spread, under further stressing, to failure.

Fig. 7—Early stage intermetallic cracking at joint interface. (a) Crack region

Fig. 8—Solder impurity cracking through overaged intermetallic. (a) Intermetallic growth in solder

Fig. 9—Crack due to cooling effects. (a) Microcracked eutectic colony boundary

Mechanically Induced Microcracks

Of the three possible sources of mechanically induced microcracks, fatigue is probably the most important area to consider. Because the other two areas are minor, they will be discussed first.

By thermal shock, one generally means sudden cooling or quenching of a solder joint during the soldering process. One must consider a solder joint as being a type of casting. If the molten solder is suddenly quenched, inadequate filling in the through hole occurs with shrinkage, leaving small internal fissures. Figure 9 is an example of a type of crack caused by the opposite effect. Too slow cooling has produced solidification shrinkage cracks, and a long grain boundary microcrack results. Wild[27] reports finding cracks induced in this manner.

No visual evidence is given here for a crack propagated through constant load. A consideration of the poor mechanical properties of solder, however, leads to a quick conclusion that constant load of a lead wire soldered into a printed wiring board will result in either creep and/or tensile shear failure.[21,27] The obvious mechanisms operating to produce cracks would be classical grain boundary, or even the interface boundary between eutectic lamella, sliding or tensile void formation.

Fatigue of solder may be the result of two things; vibration or thermal cycling. Literature indicates[9-19] that thermal cycling fatigue is the most important source. Because of the more than adequate source material available, we will only indicate here that this results from either cyclical temperatures from operational or environmental considerations, e.g., an on-off power circuit or an orbiting satellite.

Figures 1 and 3 are excellent examples of the results of thermal fatigue cycling. Here one sees the protrusions that typically result from the "back and forth" motion of the solder. Also, we can see the orientation of the crack with respect to this deformed region. Figure 3 shows, through heavy coarsening of the deformed region, how severe the deformation was.

Conclusion

Although the information given in this paper only begins to touch upon the problem of cracked solder joints, it does serve to point out some of the areas that need more consideration. Mechanisms to prevent or hinder creep and fatigue need to be investigated for strengthening of solder joints. It is hoped that this paper will act to stimulate some interest in pursuing these investigations.

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