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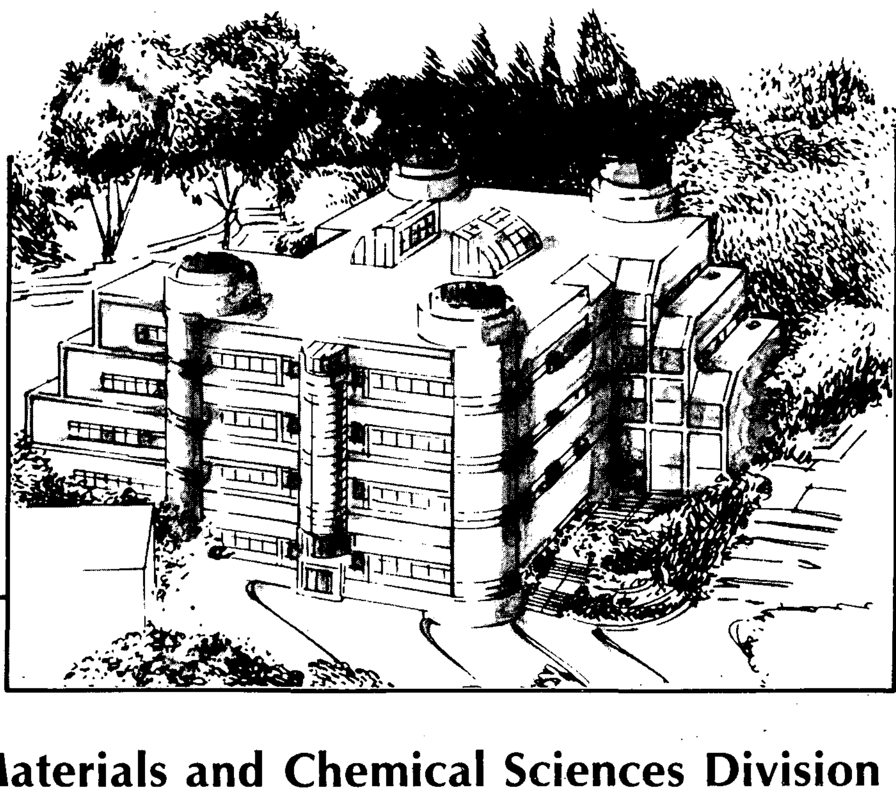

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by

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ABSTRACT

Thermal fatigue of solder joints is an important source of failure in electronic devices. Failures arise from the strain, most often in shear, imposed on the solder joint by the uneven thermal expansions of the joint constraining surfaces. Increased solder joint reliability and improved more fatigue resistant solders require and understanding of the metallurgical mechanisms operative during the fatigue cycle. The work that is reviewed here concentrates on the mechanisms of thermal fatigue and, in particular, their association with the solder microstructure. While the fatigue life of Pb-Sn solder joints is strongly dependant on operating conditions, the metallurgical mechanisms of failure are surprisingly constant for joints where the deformation occurs predominantly in shear at elevated temperatures and the solder exhibits the classic lamellar eutectic microstructure. Under these conditions, the shear strain in the joint is inhomogeneous and initiates a local recrystallization and softening of the solder microstructure. Fatigue cracks initiate in this softer microstructure to cause ultimate failure. The results outlined here identify and elucidate the role of the solder microstructure during thermal fatigue and suggest specific paths toward the design of superior solder alloys.

INTRODUCTION

This note is intended to summarize several years research into the metallurgical mechanisms of thermal fatigue in Pb-Sn solders. The central results are published in detail elsewhere. They are briefly reviewed here with references to the original work.

Solder contacts are critical to electronic packaging since they provide both the electrical and the mechanical connection between different levels of the package. As device miniaturization has led to increasingly dense electronic packages the mechanical integrity of the solder contacts has become a serious concern. A major problem is thermal fatigue, which arises from the thermal expansion mismatch between the materials joined by the solder.

The research that is reviewed here concerns the metallurgical mechanisms of the thermal fatigue of near-eutectic Pb-Sn solder contacts on copper, which is the most common class of contacts in the industry. There are two principal reasons to be concerned about the mechanisms of thermal fatigue, and address the two problems that need to be overcome to ensure joint reliability in service.

First, sound analytic models and accelerated fatigue tests are needed to guide and verify package designs. While useful tests can be designed empirically, and several have been proposed, these become uncertain when they are applied to devices, geometries or operating environments outside the set for which they have been specifically verified. A theoretical model or accelerated test is only valid to the extent that it reproduces the mechanisms that lead to failure in service; otherwise it may yield results that are badly misleading.

Second, new fatigue-resistant solders are needed to survive the severe conditions that will be experienced in very dense microelectronic packages. The design of improved solders also requires that the metallurgical mechanisms of thermal fatigue be well understood so that appropriate metallurgical modifications can be introduced to defeat them.

From the metallurgical perspective the problem of thermal fatigue in solder contacts is as complex as any fatigue problem that has been researched. Since the solder is mechanically soft and is used at a high homologous temperature (a large fraction of its melting point) deformation is introduced by plasticity and creep (stress relaxation) at both ends of the strain cycle. The cyclic deformation is affected by the fact that the solder contact is a thin layer bonded to relatively rigid materials with a complex intermetallic reaction layer at the bonding plane. The long-term deformation behavior is further complicated by the microstructural changes that inevitably occur in the solder as it is cycled and aged. A review of the literature will show that the first-order problem of fatigue crack growth at low temperature under simple periodic loading is only partly understood. There is no reliable predictive theory for thermal fatigue under creep conditions for even simple monolithic materials. The problem of predicting the rate of thermal fatigue in a solder joint is more formidable still, and is unlikely to be solved in the near future. Nonetheless mechanistic research on the fatigue of solder joints can provide valuable information to help guide the development of accelerated tests and the creation of improved solders.

MICROSTRUCTURE OF Pb-Sn SOLDER JOINTS ON COPPER

Pb-Sn solder makes a firm joint with copper through a chemical reaction that forms a thin Cu-Sn intermetallic layer at the interface. In low-Sn compositions the intermetallic is Cu_3Sn. When the Sn content is higher, as in a 63Sn-37Pb eutectic solder, the intermetallic is a double layer with a compact layer of Cu_3Sn on the copper side and a relatively rough and irregular layer of Cu_6Sn_5 on the solder side. Both intermetallics are brittle and liable to fracture when flawed or loaded in tension across the joint. Illustrative micrographs of the intermetallic layer are given in refs. [1-4].

The microstructure of the solder depends on its composition and on the rate at which it is solidified. Eutectic 63Sn-37Pb solder has a classic eutectic microstructure when it is solidified at a slow to moderate rate; as shown in refs. [5-8] it consists of grain-like eutectic "colonies" that consist of lamellae or rods of Pb-rich phase embedded in a matrix of the Sn-rich phase. In addition, small Sn precipitates are found within the Pb-rich phase. The eutectic microstructure is less well-defined in material that is solidified more quickly.

When a solder of the eutectic composition is rapidly quenched it contains an irregular distribution of islands of Pb-rich phase in a Sn-rich matrix. As the Pb content of the solder is increased the eutectic microstructure is modified by the presence of an increasing volume fraction of pro-eutectic Pb-rich grains, as illustrated in ref. [9].

MECHANISMS OF THERMAL FATIGUE IN SHEAR

Solders with 60Sn-40Pb content have a substantial fraction of the eutectic constituent in the microstructure when they are solidified at normal rates, and fail in a characteristic manner when they are tested under shear loads in thermal fatigue [8,10-15], in isothermal fatigue [9,13,14], or in creep [16,17]. The failure mechanism reflects the instability of the eutectic microstructure and the inhomogeneity of shear deformation in the solder.

The eutectic microstructure is unstable with respect to reconfiguration into a mixture of equiaxed grains of Pb-rich and Sn-rich phases. The driving force for this reconfiguration is a decrease in the total area of interface, and, hence, in the net surface energy. The reconstruction of the microstructure is significantly accelerated by plastic deformation; a eutectic Pb-Sn solder is easily recrystallized into an equiaxed microstructure by deforming it, even at room temperature. When the sample recrystallizes the flow stress of the solder decreases, and continues to decrease as the grains grow after recrystallization.

Shear deformation in the irregular microstructure of a eutectic Pb-Sn solder is inhomogeneous. It is concentrated in planar bands in the shear plane of the joint. Hence the recrystallization of a eutectic solder that is deformed in shear creates planar "coarsened bands" that lie parallel to the interface and contain equiaxed and coarsened grains. The formation of coarsened bands is a catastrophic process; since the recrystallized material is softer than the surrounding eutectic, strain concentrates in the coarsened band, causing further coarsening and strain concentration until fatigue cracks eventually form and propagate to failure. The failure mechanism is evident in laboratory specimens [8-17], and is commonly observed in device failures in carrier-to-board and pin-through-hole bonds where the joint has reasonable thickness and the eutectic microstructure is created [18-21].

A similar, but slightly modified failure mechanism applies in thin joints that solidify rapidly in normal processing. The rapidly solidified solder does not develop a classic eutectic microstructure, but rather forms an irregular mixture of Pb-rich and Sn-rich grains. This microstructure is also unstable in shear and forms coarsened bands that concentrate the strain and lead to failure. There is, however, some evidence that the failure in the rapidly solidified microstructure is delayed by a superplastic component in the deformation of the fine-grained material. While the superplastic behavior of recrystallized Pb-Sn eutectic is well-characterized [e.g. 22-28], superplasticity in fine-grained, rapidly solidified material has not been unambiguously demonstrated. The possibility was suggested by Shine and Fox [29], who used it to formulate a quantitative analysis of creep fatigue in solder; Grivas [30] has recently obtained experimental evidence that supports that hypothesis. While superplastic deformation may delay the onset of microstructural inhomogeneity and failure in thin joints, it does not suppress it in the joints studied to date. Coarsened bands eventually form, concentrate the strain, and provide the failure path.

The mechanism of fatigue in shear provides simple explanations for two phenomena that have been noted in the shear fatigue of eutectic solders.

First, fatigue resistance improves in solders that are enriched in Pb with respect to the eutectic composition. These solders contain microstructural islands of pro-eutectic Pb-rich phase, which tend to homogenize shear deformation and inhibit the development of coarsened bands. A recent study [9] suggests that the isothermal fatigue resistance of Pb-rich solders peak at about the 50Pb-50Sn composition.

Second, thickening a eutectic Pb-Sn solder joint does not improve the fatigue life nearly as much as would be suggested by the decrease in the overall shear strain. Once a coarsened band forms the shear is concentrated there, so the fatigue life depends on the local thickness of the coarsened band much more than on the overall thickness of the joint. Thickening the joint delays the formation of coarsened bands, but has a lesser effect on fatigue life once the inhomogeneous microstructure has developed.

The mechanism of shear fatigue in low-Sn solders (for example, 95Pb-5Sn) is quite different from that in eutectic Pb-Sn solders, since these do not contain the eutectic microstructural constituent. The low-Sn solders deform inhomogeneously in shear, and fail either along the shear bands [14] or through the grain boundaries of the Pb-rich grains [9]. Their relative fatigue resistance seems to depend on the test conditions. Their behavior in thermal fatigue is complicated by the strong temperature dependence of Sn solubility in Pb. Low-Sn solders solidify into a single-phase, Pb-rich solid solution. Sn-rich precipitates form within Pb-rich grains during cooling, and redissolve during heating [31,32]. The influence of this microstructural hysteresis on thermal fatigue behavior has not been studied in detail.

MECHANISM OF FATIGUE IN TENSION

The mechanisms of thermal fatigue of solder joints in tension have not been studied in as great detail as the mechanisms in shear. Limited research that has been done by the present authors [8,12]. The results suggest that fatigue failure in tension initiates more rapidly than in shear, and tends to occur through crack growth through the brittle intermetallic layer. The final fatigue failure contains cracks through the intermetallic that are joined by cracks through the bulk solder near the interface. Bands of coarsened microstructure do not form in the striking way observed for fatigue in shear. The coarsening is more general, and tends to concentrate along eutectic colony boundaries perpendicular to the interface.

The fatigue behavior of solder joints under tensile loads contrasts with that of bulk eutectic solder. The data suggest that solder joints are more liable to failure under tensile load than shear loads, while bulk solder fails more quickly in shear. The reason is the tensile failure of the brittle intermetallic layer. These results suggest that solder joints be designed to minimize tensile loading across the intermetallic. On the other hand, tensile loads are less damaging if they occur in the bulk solder away from the intermetallic, as they do, for example, in the outer regions of the solder attachment of a chip carrier to a circuit board.

TOWARD FATIGUE-RESISTANT SOLDERS

A major impetus for mechanistic studies of solder fatigue is the need to develop new solders with improved fatigue resistance in the challenging environments that will be encountered in future microelectronic devices. To improve the fatigue resistance of low-melting, eutectic solders one needs to defeat the metallurgical mechanism of shear fatigue. This mechanism involves two processes, which happen in series: shear deformation develops in an inhomogeneous pattern and triggers recrystallization which forms soft, coarsened bands. It seems evident that fatigue resistance can be improved by minimizing the inhomogeneity of plastic deformation or by inhibiting recrystallization and grain growth within inhomogeneous bands.

Two metallurgical techniques have been identified to promote homogeneous deformation during shear of the solder joint. The first is the introduction of constituent particles of different composition or microstructure to break up planar bands of shear. In Pb-rich solders islands of pro-eutectic Pb-rich phase serve this function, and are apparently responsible for the very high fatigue resistance of 50Pb-50Sn solders [9]. Constituent phases formed by third elements or introduced as dispersants can also be used for this purpose. The second is to replace the eutectic microstructure with an equiaxed, fine-grained microstructure that naturally deforms in a uniform and, preferably, partially superplastic mode. Recent research suggests that this may be made possible in thin joints of suitable composition by controlling the cooling rate during solidification. It is also possible to obtain a uniform microstructure by a combination of deformation and recrystallization after the joint is made.

To inhibit recrystallization within the deformed bands one may employ chemical additives that are known to delay recrystallization or grain growth in the Pb-Sn system. Indium and cadmium are promising additives for this purpose, and have been used with some success in initial work in this laboratory [17].

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