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OBSERVATIONS ON THE MECHANISMS OF FATIGUE IN EUTECTIC PB-SN SOLDER JOINTS

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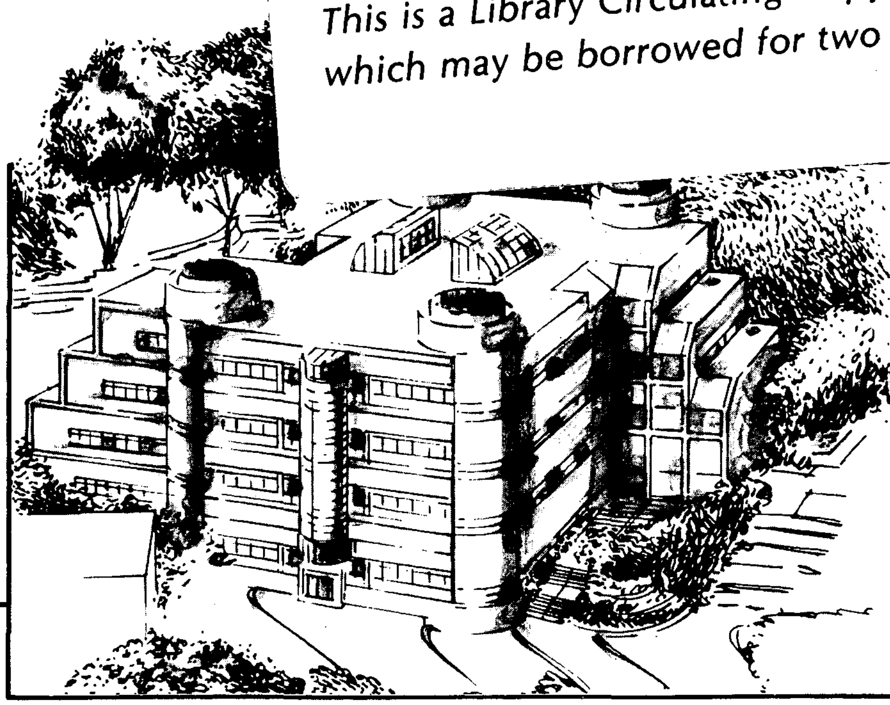

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Observations on the Mechanisms of Fatigue in Eutectic Pb-Sn Solder Joints

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Near-eutectic Pb-Sn solders are widely used for joints in electrical devices. These are liable to failure by thermal fatigue during operation of the device. Since the thermal fatigue load is often in shear, the mechanisms of thermal fatigue in shear are of particular interest. Recent research has shown that the thermal fatigue of eutectic solders in shear is preceded by the formation of bands of coarsened material in the eutectic microstructure, which concentrate the deformation and cause the nucleation of fatigue cracks. Such coarsened bands are also observed in isothermal fatigue and unidirectional creep in shear. Since creep experiments are relatively simple to conduct and analyze, these have been used to study the formation and growth of coarsened bands. The mechanism includes three steps: the formation of inhomogeneous shear bands, the onset of recrystallization in the shear band to create a planar region of coarsened material, and the propagation of the coarsened band by progressive recrystallization at its tip. The results are applied to thermal fatigue and some of their implications are discussed.

1. Introduction

Near-eutectic lead-tin solders have been widely used for electrical contacts because of their low melting points, good wettability on copper and a variety of other metals, good plasticity, good corrosion resistance, and reasonable electrical conductivity. However, some of the very properties that make these solders desirable, their malleability and low melting points, also make them liable to failure by thermal fatigue in service. The design of reliable solder joints requires an understanding of solder fatigue that is sufficient to guide the development of accelerated tests that predict fatigue life. Advanced devices may also require the development of new, fatigue-resistant solder materials. An accelerated fatigue test is likely to be accurate only to the extent that it correctly scales the metallurgical mechanisms of fatigue. The fatigue resistance of solders is determined by their ability to resist the mechanisms of fatigue. Hence both the design of probative fatigue tests and the development of improved solders require that the metallurgical mechanisms that govern fatigue failure be well understood.

The most common cause of solder fatigue in electronic devices is the thermal expansion mismatch between the components joined by the solder. When the device is heated, either by the operating current or by a change in the ambient temperature, differential thermal expansion causes a relative displacement of the components across the joint that strains the solder. Subsequent cooling when the device is turned off or returned to its original ambient reverses the strain, completing a fatigue cycle. The details of the cyclic strain depend on the geometry of the joint and the operating characteristics of the device.

However, the strain is often very nearly a simple shear, as illustrated in Figure 1 for a simple chip-to-substrate contact.

The development of a mechanistic theory of solder fatigue is complicated by several factors. First, the fatigue cycle of greatest interest is a cyclic shear strain. Shear fatigue involves rather different deformation mechanisms than fatigue under tensile loads, which have been emphasized in most fundamental studies of fatigue behavior. Second, the fatigue is driven by temperature. Since the mechanical properties of the solder are temperature-dependent they change continuously during the fatigue cycle. Moreover, in most cases of interest the peak temperature approaches the melting point of the solder with the consequence that high-temperature creep is an important deformation mode. Third, the relatively high homologous temperatures reached during the fatigue cycle cause microstructural changes in the solder which alter its mechanical properties. Microstructural changes are particularly likely since the solder is initially in an as-solidified structure that is unstable under thermomechanical processing. Fourth, the solder is not a bulk sample, but is usually a stubby ball or thick film whose faces are constrained by the wetted interfaces of the joint. The wetted interfaces often have a complicated metallurgical structure of their own. Finally, Pb-Sn solders are liable to corrosion and chemical attack, which can influence the rate of fatigue if the joint is not isolated from aggressive environments.

The complexity of solder fatigue has the probable consequence that a reasonably complete mechanistic theory will not be constructed for some time. However, recent fundamental research has helped to clarify some of the important mechanisms involved. Among the most interesting of these is the microstructural instability that appears to govern thermal fatigue in near-eutectic Pb-Sn solders [1-3]. Fatigue cracking in a eutectic solder in cyclic shear is often preceded by the formation of microstructural bands of coarsened grains that lie roughly parallel to the plane of maximum shear. Fatigue cracks form in these bands and propagate along them to ultimate failure. In the body of this paper the phenomenon of microstructural banding is described and illustrated, and the probable mechanisms of banding are discussed. While only the Pb-Sn system is treated here, the phenomena described should be observed during creep or fatigue when any eutectic microstructure is subjected to shear loads at high homologous temperatures.

2. The Microstructure of Eutectic Pb-Sn Solder Joints

To discuss the mechanisms of fatigue of a eutectic solder joint it is first necessary to describe the microstructure of the joint. Both the microstructure of the solder phase and the wetted interface are important. For specificity we describe the as-solidified microstructure of a 60Sn-40Pb solder on copper.

a. The wetted interface. The wetting of Cu by Pb-Sn solder is primarily due to the formation of Cu-Sn intermetallic films at the interface. In the case of 60Sn-40Pb solder the intermetallic layer is a bilayer of two intermetallic films [4,5], as shown in Figure 2. The inner film, adjacent to Cu, is a thin, coherent layer of Cu_3Sn which is relatively uniform in thickness over the surface. The outer film, adjacent to the solder, is a thicker layer of

Cu_6Sn_5 which has an irregular outer boundary that contains rounded protrusions and needle-like whiskers that thrust out into the solder. Almost all of the intermetallic growth occurs while the solder is molten. The thickness of the intermetallic layer depends on the temperature and time of exposure to the molten solder.

The nature of the intermetallic layer is sensitive to the composition of the solder. When the solder composition is 95Pb-5Sn, for example, only the Cu_3Sn intermetallic is present.

b. The solder phase. The as-solidified microstructure of 60Sn-40Pb solder is illustrated in Figure 3. The typical microstructure includes isolated particles of pro-eutectic Pb-rich phase amongst a eutectic mixture of the Sn-rich and Pb-rich phases. Closer examination reveals that the Pb-rich phase contains small, plate-shaped Sn-rich precipitates [6]. These form during cooling from the eutectic solidification temperature to adjust the composition of the Pb-rich phase to its equilibrium value. The eutectic microstructure usually consists of "colonies" readily distinguished by the uniformity of phase distribution within such a colony and the presence of a "colony boundary". The phase distribution within a colony may be lamellar or globular.

Pb-Sn solders on Cu also contain embedded precipitates of Cu_6Sn_5 intermetallic, which have the form of long, hexagonal rods that are often hollow in the core. Prior research [5] suggests that these are intermetallic whiskers that formed on the Cu interface when it was originally wet by the solder, but broke off the surface and were trapped in the solder as it solidified.

3. The Mechanism of Thermal Fatigue in Shear

The specimen that is diagrammed in Figure 4 was used to investigate the metallurgical mechanisms of thermal fatigue in shear [1]. The specimen is a thin, three-layer sandwich with Cu outer layers and a Cu-coated Al inner layer, joined with solder. When the specimen is heated the thermal expansion difference between the Cu and Al layers imposes a shear strain on the solder whose magnitude increases, for the most part, linearly from the center to the ends of the sample. Samples of this configuration were thermally fatigued by alternate immersion in hot and cold baths. The response of the specimen was monitored by metallographic analysis after exposure to a selected number of thermal cycles. Detailed experimental procedures and results are reported elsewhere [1,7].

A typical result of these experiments is presented in Figure 5, which illustrates the development of growing thermal fatigue cracks in the high-strain region of specimens that were thermally cycled between -55°C and 125°C to a peak shear of approximately 20%. The first apparent change in the specimen is metallurgical, and is the appearance of a continuous band through the eutectic microstructure within which the Pb- and Sn-rich regions are significantly coarsened with respect to the surrounding material. The band lies along the length of the bar, is slightly offset from the interface and is roughly parallel to the plane of maximum shear. As thermal cycling continues cracks appear within this band and merge to form a growing thermal fatigue crack. The cracking mechanism, which is illustrated in Figure 6, involves the intergranular fracture of Sn-rich grains followed by the gradual failure of the intermediate Pb-rich material.

Examination of a number of specimens given various thermal fatigue cycles suggests that this mechanism is general for the thermal fatigue of eutectic solder in shear, even when the peak temperature is as low as 35°C.[1] The formation of a planar band of coarsened material precedes the nucleation of a fatigue crack, which grows primarily through intergranular cracking of the Sn-rich grains. An examination of published microstructural studies of eutectic solder joints that failed under thermal fatigue in shear [3,8-9] reveals the same phenomenon; the fatigue crack propagates through a band of microstructurally coarsened material.

Given the formation of a planar band of microstructurally coarsened material on a plane of maximum shear in eutectic solder, it is not surprising that the fatigue crack forms and grows there. It is well known [10] that the replacement of the eutectic microstructure by a coarse microstructure of more equiaxed gains weakens the solder. Hence the cyclic shear strain is expected to concentrate in the coarsened band and induce fatigue there. The important question is the mechanism that creates the coarsened band in the first place. That issue has been the subject of our recent research.

To gain insight into the conditions that govern the formation of bands of coarsened microstructure in eutectic solder, four other load geometries have been investigated: (1) thermal cycling in the absence of load; (2) thermal fatigue in tension; (3) isothermal fatigue in shear; (4) unidirectional creep in shear. The results of these studies [11,12] show that a shear strain of the solder joint promotes the formation of coarsened bands. Conditions (3) and (4) involve shear loading and lead to the formation of coarsened bands; conditions (1) and (2) do not. When the solder is thermally cycled in the absence of an applied load the microstructure coarsens, but the coarsened regions are irregular in shape and are randomly distributed through the volume. When the solder joint is cycled under a tensile load perpendicular to the plane of the joint coarsened bands are not observed. In fact, the fatigue crack often propagates through the brittle intermetallic at the interface rather than through the solder.[7]

It is particularly interesting that coarsened bands form during unidirectional creep in shear. Given the relatively high homologous temperatures that pertain during thermal fatigue of eutectic solders creep deformation is certainly involved. Moreover, unidirectional creep experiments are easily done under carefully controlled conditions that allow detailed study of the progress of deformation and the evolution of the microstructure. For these reasons we have recently emphasized unidirectional creep experiments as a method of studying the mechanism of formation of microstructurally coarsened bands.

4. The Formation of Coarsened Bands during Creep in Shear

The sample used for the creep (and isothermal fatigue) experiments is diagrammed in Figure 7. It is a thin, three-layer copper sandwich with solder layers between each of the copper plates. The sample is slotted, as shown in the figure, so that the solder material between the slots transmits the load in nearly simple shear when the sample is pulled in tension. Creep experiments are conducted by applying a constant tensile load to the specimen, which imposes a constant nominal shear stress on the central joints that transmit the load. The shear strain in the solder is then measured as a function of time. The tests determine the steady-state creep rate of the solder as a function of the nominal shear stress and temperature for comparison with conventional steady-state creep data. This data will be published elsewhere. In this paper we are mainly concerned with the mechanism of formation of coarsened bands during creep in shear.

The presence of coarsened shear bands in the crept specimens is documented in Figure 8b, which shows a coarsened band parallel to the wetted interface, note that the coarsened band is nearly straight. A higher magnification photograph, Figure 9, shows that the material within the coarsened band consists of relatively large, equiaxed grains which resemble the grains formed by recrystallization of mechanically worked Pb-Sn eutectics [10,11]. This is the normal microstructure within a coarsened band. Eventually, cracks and cavities form within the bands and, as in thermal fatigue, the fracture initiates through intergranular cracking of Sn-rich grains which induces failure of the nearby Pb-rich material.

The advantage of the creep experiment is that it permits a sequential study of the formation of the coarsened bands. The sequence appears to include three stages: (1) the establishment of an inhomogeneous deformation pattern of concentrated shear bands parallel and perpendicular to the joint interface; (2) the initiation of a coarsened band by recrystallization of the eutectic microstructure where the shear band intersects the lateral free surface of the solder joint; (3) the propagation of the coarsened band through progressive recrystallization along a planar zone of concentrated shear parallel to the interface of the joint. The three stages are discussed in more detail below.

The development of an inhomogeneous shear deformation pattern is a characteristic of the creep of eutectic solder, and is also observed in fatigue at moderate to high temperatures [1,2,12]. The pattern is easily revealed by polishing the surface of the solder joint prior to testing and observing the surface relief that appears as the specimen deforms. The most common pattern found in this work is illustrated in Figure 8a, which shows a specimen crept to a total strain of 20% at a strain rate of approximately 10^{-5} sec^{-1}. The pattern includes a nearly straight band of deformation that lies parallel to, but slightly displaced from the interface together with several irregular deformation bands that lie approximately perpendicular to the interface and cross the solder joint. A metallographic examination of the same surface after a light polish and etch reveals the correspondence between the deformation, Figure 8a, and the location of the coarsened band, Figure 8b. Closer inspection shows that the parallel band in Figure 8 crosses eutectic colonies while the perpendicular bands tend to follow colony boundaries. A slightly different behavior is observed at very low creep rates, 10^{-8} sec^{-1} (Figure 10a and b). In this case the parallel deformation band has an irregular shape and follows primarily colony boundaries.

In all cases the parallel deformation band originates at one side of the lateral surface of the solder joint. Finite element analyses [13] suggest that the point of origin is near the principal stress concentration point in the sample. The coarsened band that leads to fracture in the sample is always coincident with the parallel deformation band described above, and forms first at the terminus of the deformation band at the free surface, Figure 11a. It then slowly grows along the deformation band into the sample. Figure 11b, for example, shows the partly developed coarsened band of Figure 11a that terminates in the solder.

The mechanism that initiates the coarsened band seems straightforward. It is well known [10,11] that the eutectic microstructure in the Pb-Sn system is unstable with respect to recrystallization if it is deformed at a high homologous temperature or exposed to high temperature after deformation. The inhomogeneous shear strain that develops during creep creates a band of concentrated plastic deformation, which is greatest at the free surface near the stress concentration point. The eutectic recrystallizes there to relieve the accumulated deformation. Since the deformation is local and largely confined to a thin band, only this band of material recrystallizes.

The mechanism of growth of the recrystallized band also seems straightforward. The band grows by the progressive recrystallization of the deformed material. Recrystallization occurs predominantly at the tip of the planar band of previously recrystallized material, and is expected to appear there because this should be the most highly deformed element of material. Since the recrystallized material is soft compared to the eutectic material surrounding it, a narrow band of recrystallized or coarsened material in a eutectic matrix behaves mechanically very much like a narrow crack. Since the applied stress is a simple shear in the plane of the crack the strain field at the crack tip is a mode II deformation zone. The plastic strain field for a mode II crack has been solved for a Von Mises material by McClintock, et al. [14] and is diagrammed in Figure 12. Note that the deformation field is narrow and tends to confine the deformation to the plane of the crack. The next increment of recrystallization near a propagating band of recrystallization that behaves like a mode II crack should occur in the most highly strained material, which lies in the plane of the crack near the crack tip. It follows that the recrystallized band tends to remain plane and narrow while it extends itself along a shear plane, as is observed.

This picture requires a slight modification when the shear stress, and hence the shear strain rate, is small. A slow strain rate can be achieved through a sliding deformation at the colony boundaries that is analogous to the grain boundary sliding observed in the creep of polygranular materials. The phenomenon of colony boundary sliding is relatively easy to observe in eutectic solder, by deforming the solder slightly to introduce a residual stress and then polishing its surface. A surface relief that outlines the colonies gradually appears on the polished surface as the sample deforms to relieve the residual stress. The rate of colony boundary sliding is relatively slow, however, since it must be accompanied by some plastic deformation or diffusional creep to maintain the geometric integrity of the irregular colony network. The colony boundaries are favored sites for microstructural coarsening since the eutectic pattern is broken there, and the boundary can thicken and coarsen by consuming the adjacent eutectic in the colonies.

When the rate of deformation is slow the dominant deformation mechanism tends to be colony boundary sliding. In this case the shear band, and hence the coarsened band in the microstructure, tends to follow the colony boundaries. When the shear strain rate is very slow, as it is, for example, in the sample shown in Figure 10, the dominant coarsened band follows the network of colony boundaries that most nearly approximates a plane near the joint interface. In all cases studied to date the secondary shear bands and coarsened bands perpendicular to the joint interface follow colony boundaries.

5. Discussion and Conclusion

The deformation and coarsening patterns observed in the creep specimens resemble those that appear during both isothermal and thermal fatigue, though the fatigue deformation is more complex and the deformation and coarsening patterns are less well-defined. The mechanism of formation and growth of the coarsened bands appears to be the same in all three cases. An inhomogeneous shear deformation pattern develops, and creates a concentrated shear band in the solder parallel to the joint interface. The accumulating deformation causes recrystallization within the shear band (or simple coarsening where the shear band lies in a colony boundary). Because of its relative softness the coarsened band behaves very much like a mode II crack, and extends itself by recrystallizing or coarsening the material in the plane immediately ahead of its tip so that it eventually traverses the solder. The concentrated strain in the soft coarsened region induces cracking at the boundaries of the Sn-rich grains, forming a fatigue crack that propagates along the coarsened band to final failure.

Assuming that this fatigue mechanism governs the shear fatigue of solder joints, it constrains the design of accelerated solder fatigue tests and suggests metallurgical paths toward solder compositions with improved fatigue resistance.

If an accelerated solder fatigue test is to give reliable results it must accelerate the mechanism of fatigue without changing it. It should, hence, reproduce the microstructural changes that are associated with thermal fatigue on an accelerated time scale. Since it often requires years to test a solder joint to failure under actual service conditions, it is usually impractical to conduct tests to failure, or even to gather the statistics necessary to ensure that a particular accelerated test is trustworthy. However, the microstructural changes that govern thermal fatigue begin at times that are short compared to those required for fatigue failure. If those microstructural changes can be identified with confidence, as there is reason to hope, accelerated fatigue tests can be qualified on the basis of their ability to reproduce the important microstructural changes in accelerated time.

Regarding the design of solders with improved fatigue resistance in shear, the present results suggest that the critical need is to suppress the formation of the coarsened bands that govern fatigue failure. There are at least two approaches to this problem. The first is to produce a solder that deforms more homogeneously in shear, thereby suppressing the concentrated shear bands that lead to bands of coarsened material. The second is to minimize the rate of recrystallization or coarsening in deformed material. Both of these approaches are currently under investigation.

A third possible application of these results was suggested by M. Wolverton of Texas Instruments (and, subsequently, by others). Since the formation of coarsened bands in the microstructure precedes thermal fatigue failure in shear, if one could identify a non-destructive test that would detect the state of development of the coarsened bands this test could be used to inspect solder joints in critical devices and anticipate fatigue failures. The unsolved problem is the identification of a suitable non-destructive test.

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Figures

1. Schematic illustration of the shear that develops in a solder joint between a chip and substrate when the device is heated by operatng current or a change in ambient temperature.

2. Optical micrograph showing a cross-sectional view of a 60Pb-40Sn/Cu interface. Two intermetallic layers lie in the interface. The inner is Cu_3Sn, the outer is Cu_6Sn_5.

3. Optical micrograph showing a typical as-solidified microstructure of 60Pb-40Sn. The dark phase is Pb-rich. Several distinct colonies appear, separated by colony boundaries.

4. Diagram of the specimen used for thermal fatigue studies.

5. Sequence of thermally fatigued specimens showing the development of a coarsened band and associated fatigue crack.

6. Optical micrograph of a coarsened band showing the coarse grain structure and intergranular fracture between Sn-rich grains.

7. Sample configuration used for isothermal creep experiments. Due to the slot configuration cut in in sample, when the sample is pulled in tension the solder regions between the slots are strained in nearly simple shear.

8. a. An SEM micrograph of a polished solder joint crept in shear at 75°C at a strain rate of 10^{-5} sec^{-1}. b. The locallized deformation is revealed by surface relief on this joint prior to polishing.

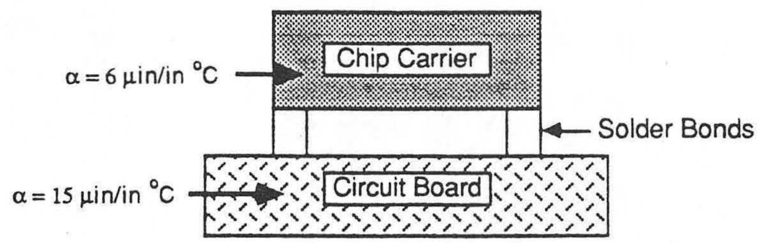
9. Detail of the coarsened band at higher magnification (optical) showing its definition and the presence of equiaxed grains apparently formed by recrystallization.

10. a. The shear deformation pattern revealed by surface relief on a specimen crept at a strain rate of 10^{-8} sec^{-1} at 75°C. b. The same specimen after a light polish. Note the correspondence between defromation path and coarsened regions along colony boundaries.

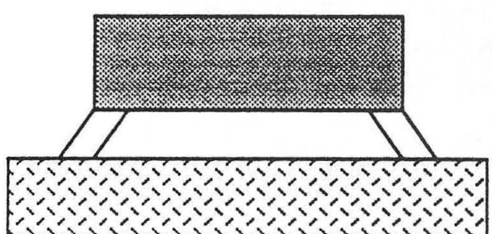
11. a. Optical micrograph showing initiation of the coarsened band at a free surface. b. The same coarsened band propagates along the length of the joint terminating within the solder.

12. The plastic deformation field ahead of a mode II crack in a Von Mises material (after McClintock, et al. [17])

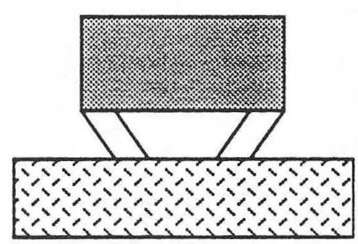
Origin of Thermal Fatigue



Electronic Package
at Room Temperature



Package at high Temperature
side of cycle (125 °C).



Package at low Temperature
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Figure 1

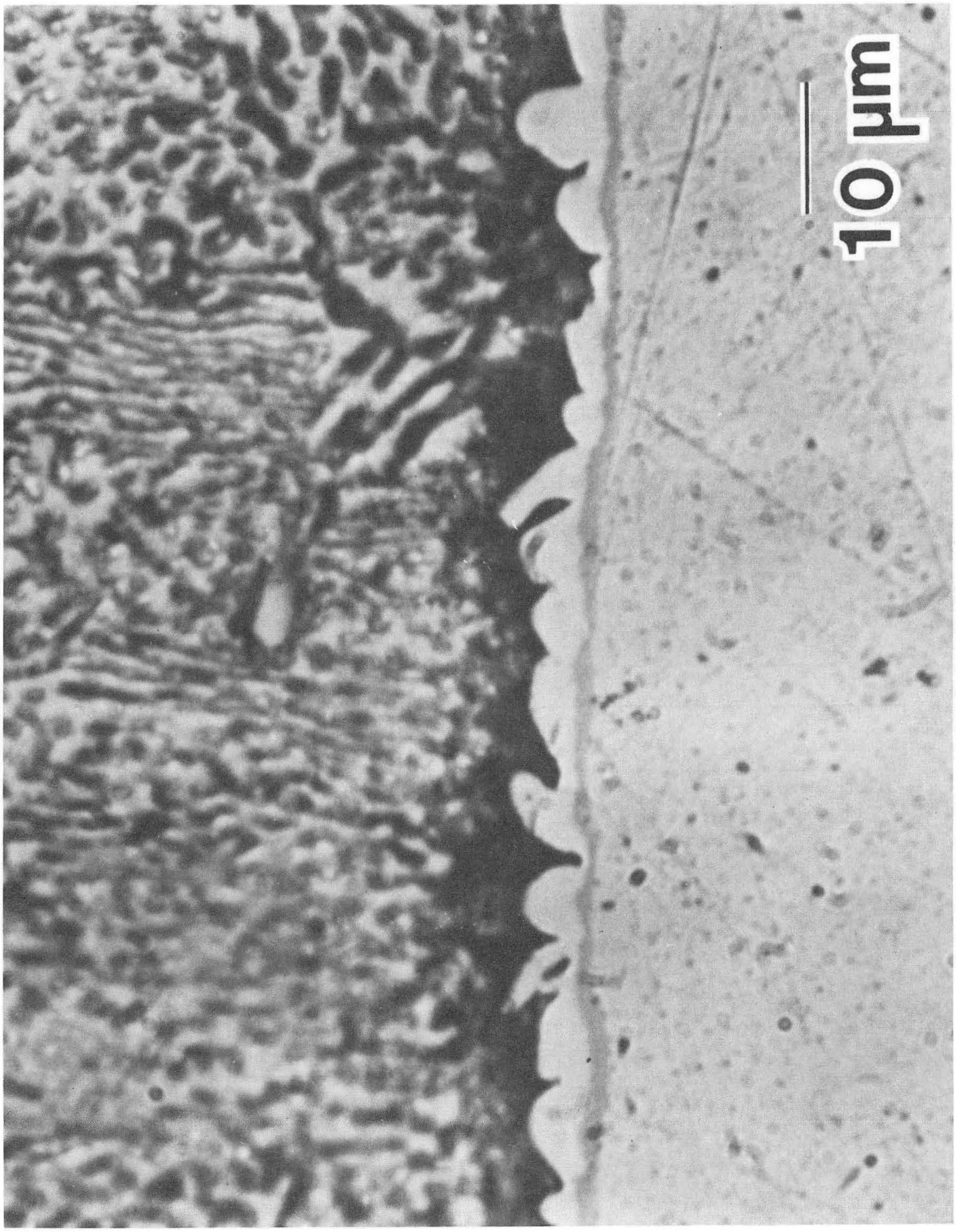

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Figure 2

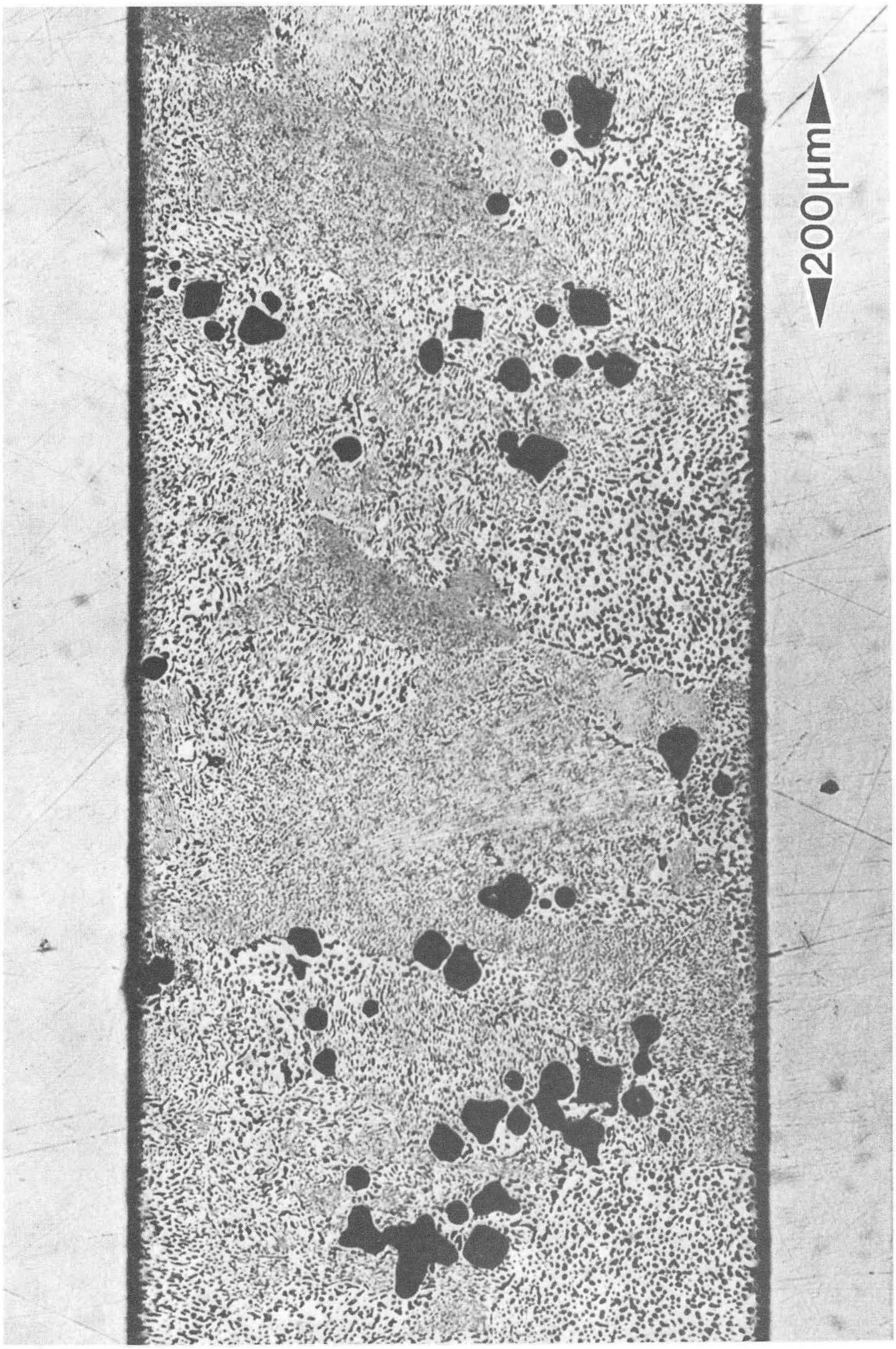

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Figure 3

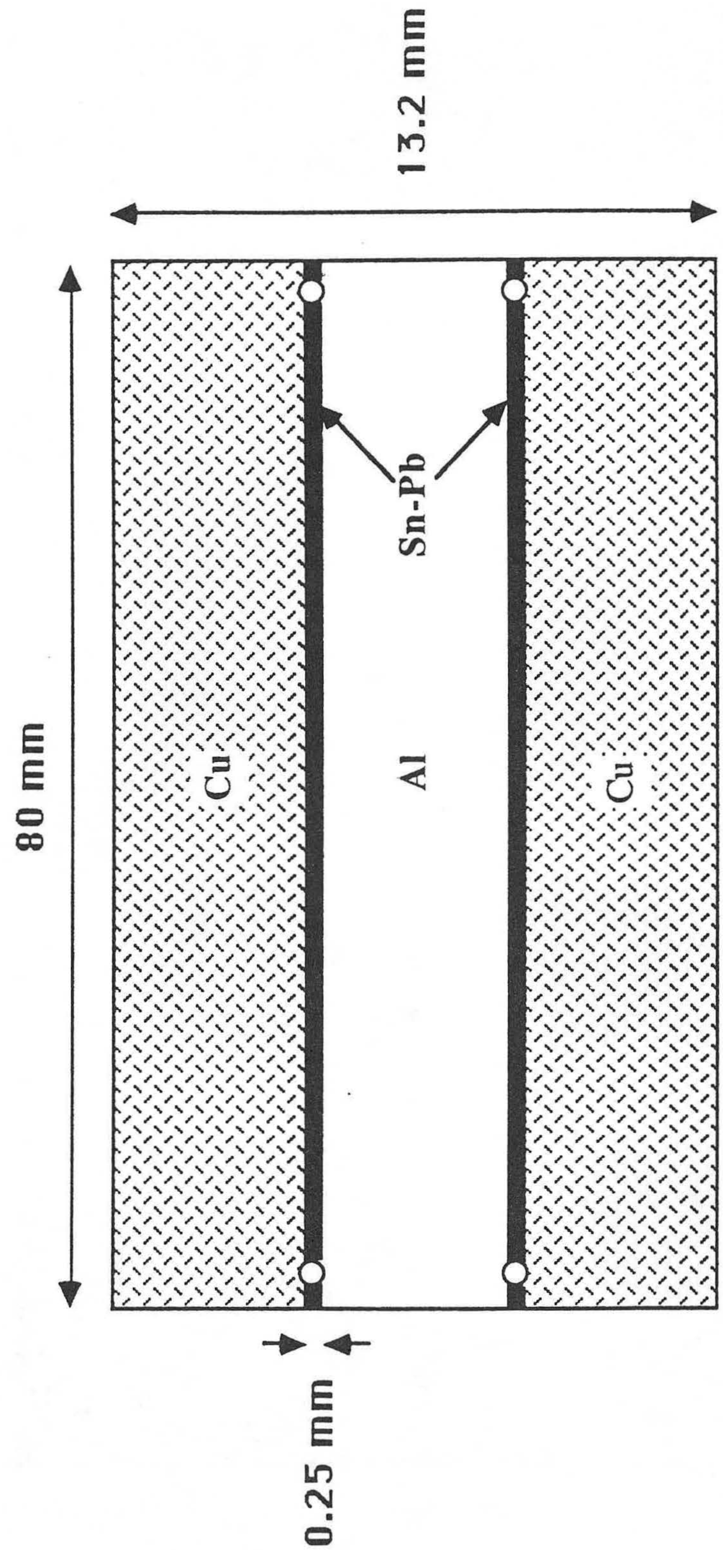

Figure 4

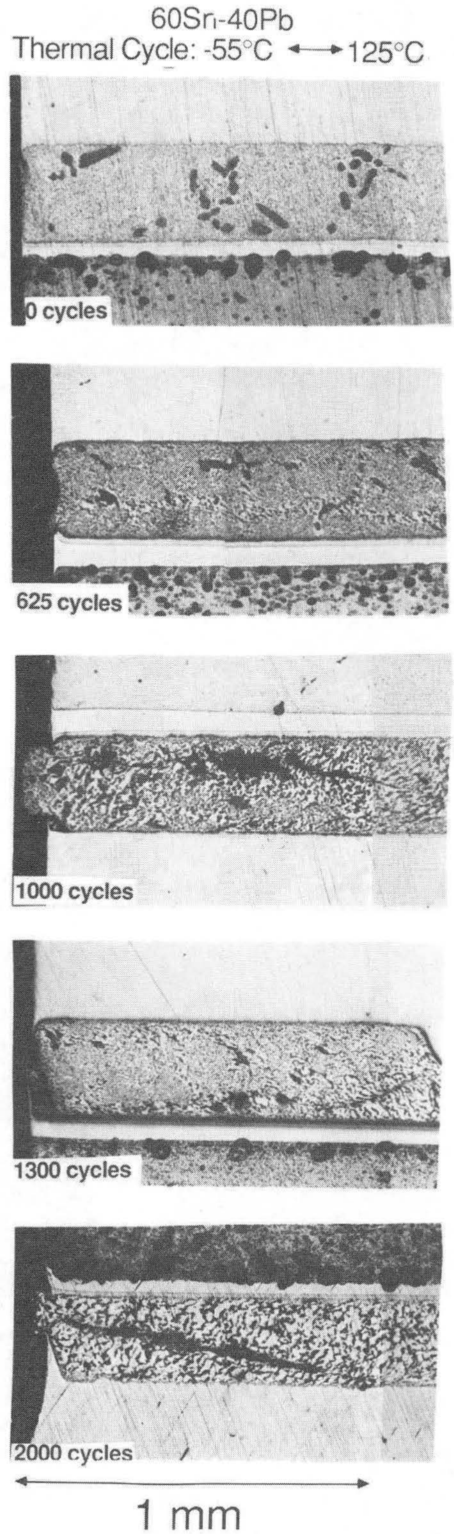

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Figure 5

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Figure 6

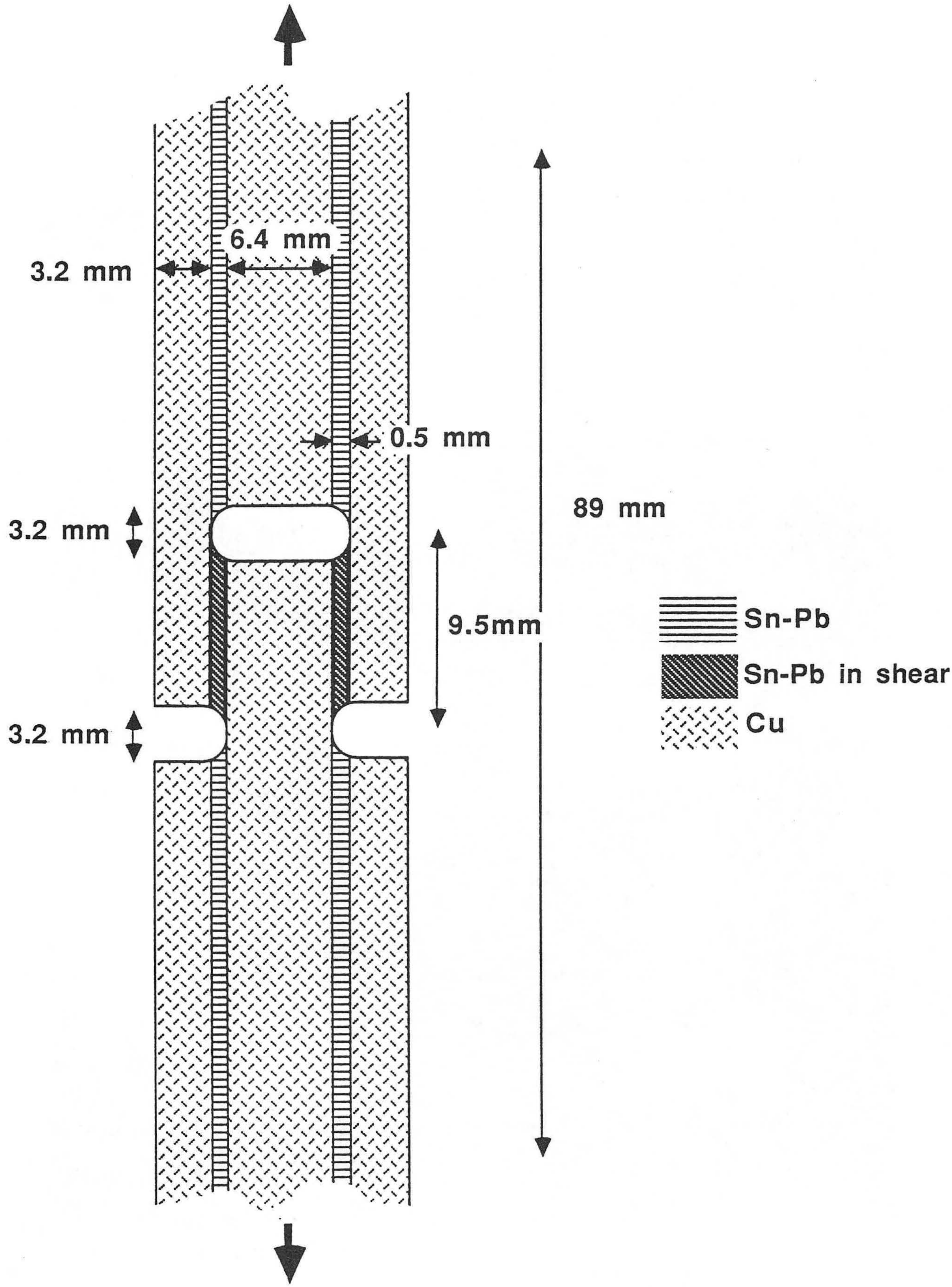

Figure 7

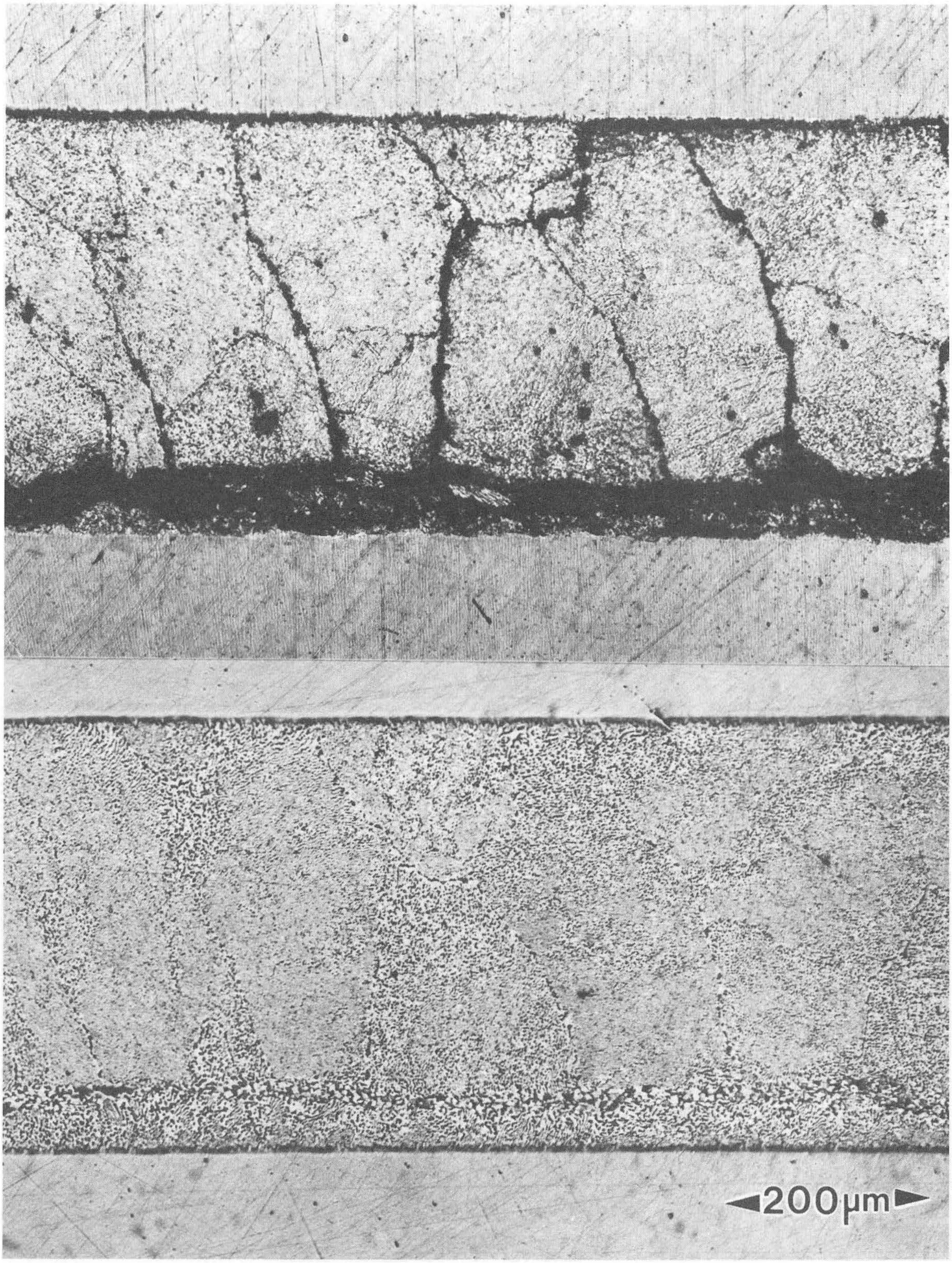

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Figure 8

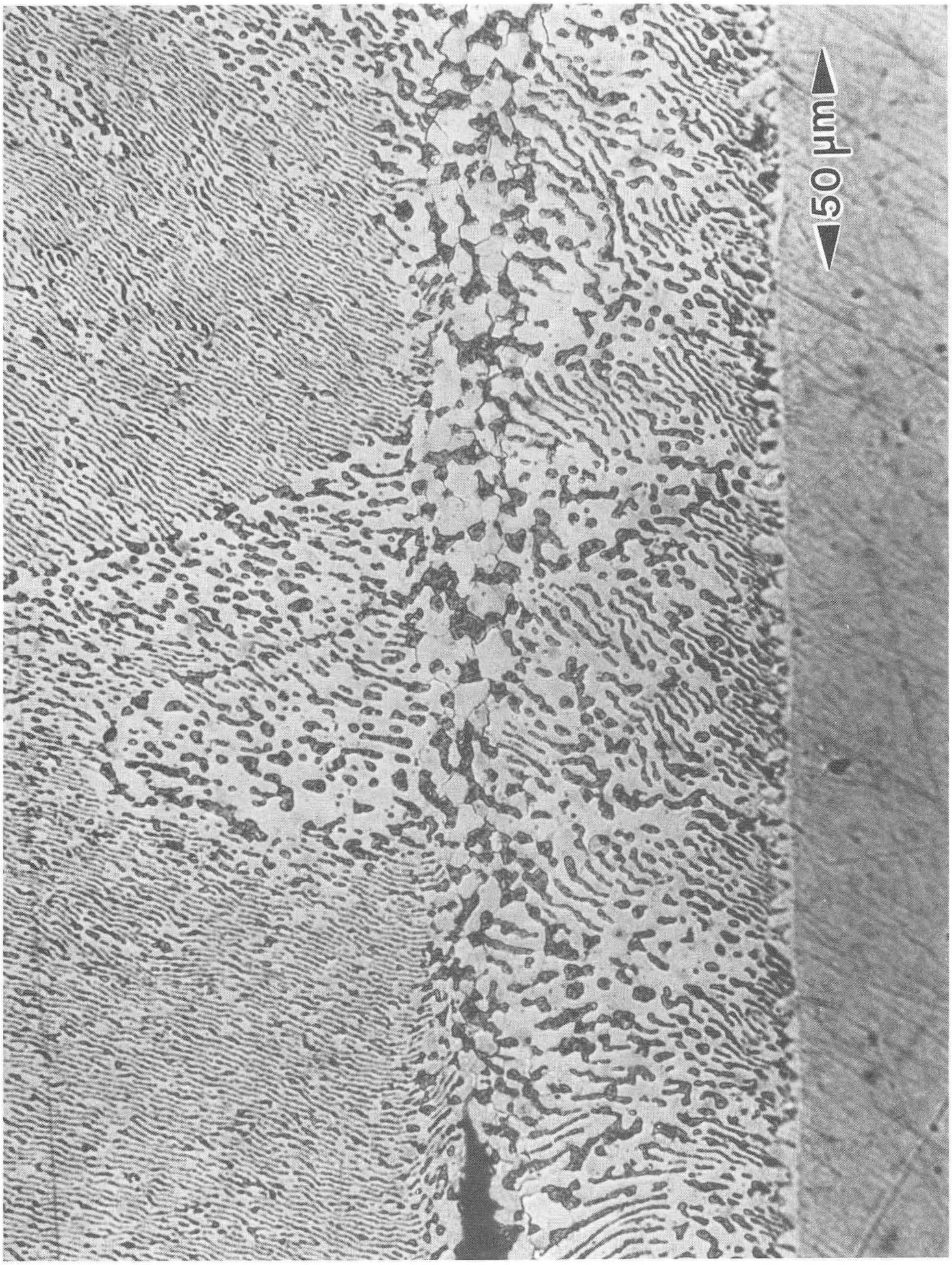

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Figure 9

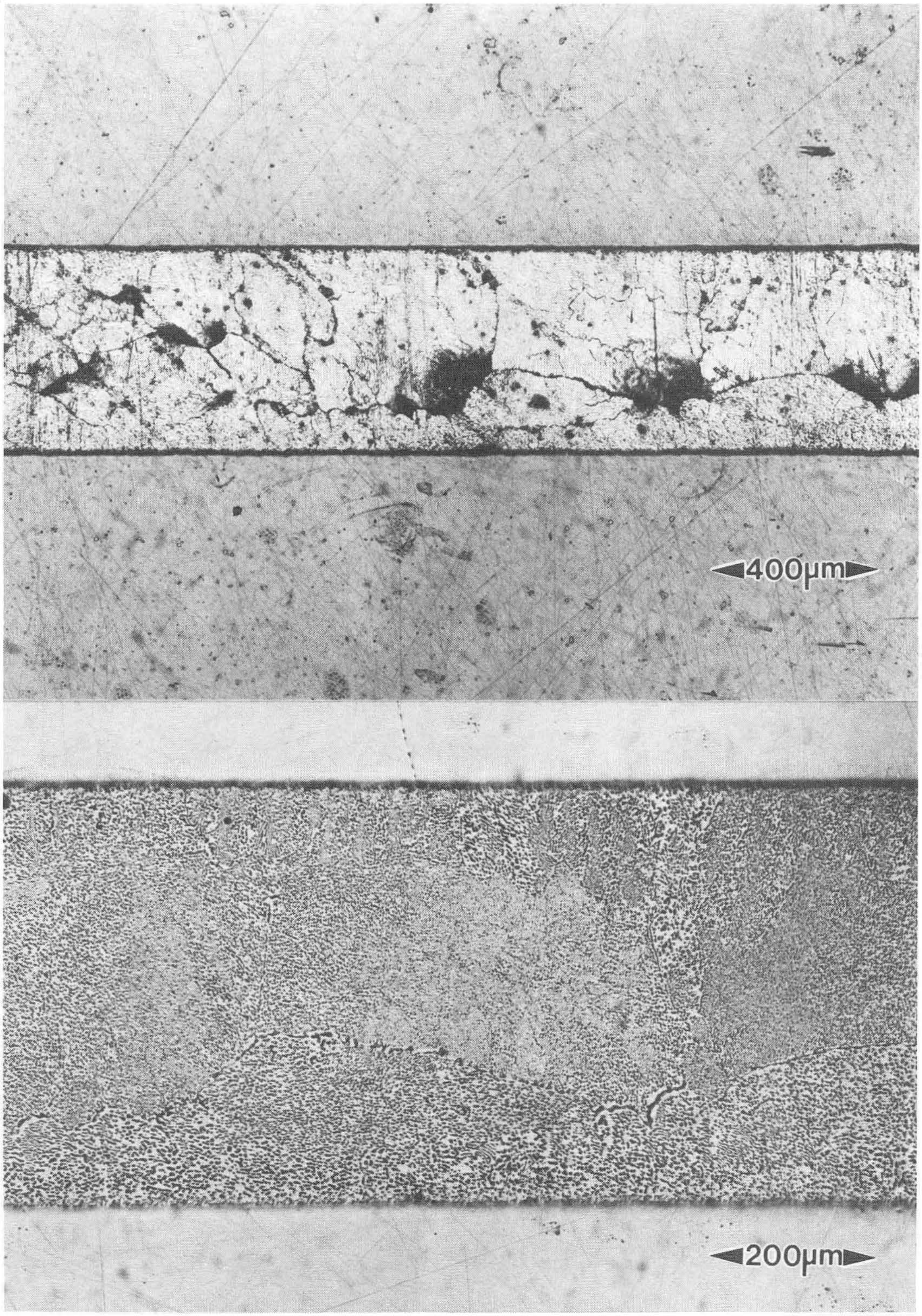

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Figure 10

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Figure 11

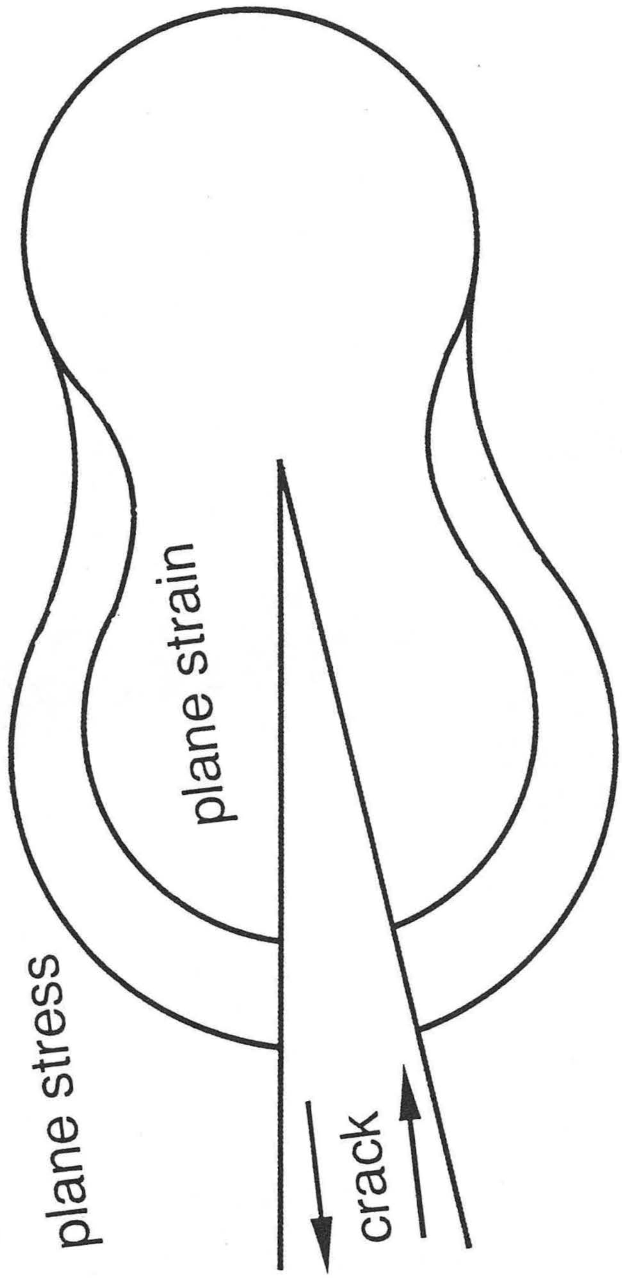

Figure 12

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