Fig. 1 — Pure indium melts at a temperature of 156.7°C (314°F). Image courtesy Indium Corp. of America.

Indium solders

Giles Humpston
Tessera Inc.
San Jose, California

David M. Jacobson
Buckingham Chilterns University College
High Wycombe, England

Indium-base solders share the common characteristics of low melting point (Fig. 1) and extreme softness and ductility. Moreover, it remains ductile even at cryogenic temperatures.

The mechanical properties are mostly a reflection of the fact that at room temperature, indium solders operate at a very high homologous temperature. That is, 25°C (77°F, 298K) is close to the melting point when expressed in Kelvins. At high homologous temperatures, the rate of solid-state diffusion in metals with simple crystal structures is sufficiently fast that microstructural changes can occur in time scales that are comparable to changes in the service environment of joints in components.

This is exemplified by the stress-strain curve of a thick indium soldered joint and the continuum between stress-strain and creep data given in Fig. 2 and 3, respectively. This means that recovery and recrystallization occur as fast as work hardening is induced, and mechanical failure of joints made of indium-base solders tends to be caused by stress overload or unidirectional creep.

The ready creep of indium solders implies that joints are unlikely to fail on thermal cycling unless the load-displacement curve is asymmetric. It follows that indium solders are well suited for making joints between dissimilar materials that will be subject to thermal cycling. In fact, creep in joints made with indium solders can usually take place sufficiently fast to ensure that the stress is always close to zero, with roughly 80% stress relaxation occurring within seconds of a step change in strain. In that case, the solder will not work harden. If joints are suitably designed to take advantage of these

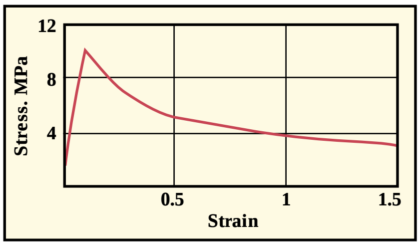

Fig. 2 — Shear stress-strain curve for a 500 µm thick indium tin (In-48Sn) joint held at 40 °C (104 °F) ambient and strained at a rate of 5 x 10^{-4}/s. Adapted from Freer Goldstein and Morris Jr. [1994]

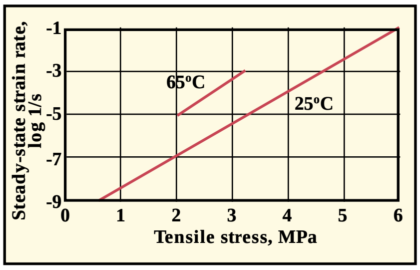

Fig. 3 — Continuum between stress-strain and creep data for indium-tin eutectic solder (In-48Sn) at room and elevated temperature. Adapted from Darveaux and Murty [1993]

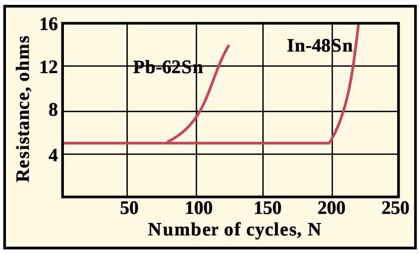

Fig. 4 — Resistance of a flip-chip daisy chain between silicon and alumina, versus the number of cycles (N) of a thermal shock test +25 to –196 °C, 30 sec dwell for the solders indicated. Adapted from Shimizu et al. [1995]

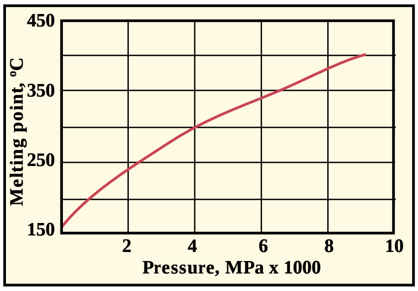

Fig. 5 — Melting point of indium as a function of pressure. Adapted from Kennedy and Newton. [1963]

Composition and melting ranges of indium-base solders

Composition, %	Melting range, °C	Melting range, °F
In-50Pb	178-210	352-410
In-30Pb	165-172	329-342
In-3Ag	141	286
In-5Ag-15Pb	142-149	288-300
In-40Sn-20Pb	121-130	250-266
In-49Sn	120	248
In-67Bi	110	230
In-34Bi	72	162
In-32.5Bi-16.5Sn	60	140

beneficial thermomechanical characteristics, indium solders can provide superior life (Fig. 4).

Failure modes

When indium soldered joints do fail, the mechanism is predominantly by classical creep rupture, which has its origins in the nucleation and coalescence of cavities that arise from the material redistribution associated with stress relaxation. In contrast, tin-base solders, when subject to conditions of low-cycle (low-strain rate) fatigue, fail because the plastic deformation in the solder leads to microstructural changes in the region of maximum strain. Internal cavities then develop, which first coalesce to form voids and then grow into cracks.

Indium-base solders for optoelectronic and photonics applications can also fail by a process known as phase segregation. This develops when an extreme and unidirectional electrical and / or thermal gradient is sustained across a joint. The result is migration of indium toward one joint interface, and the accumulation of voids at the other, until the joint fails. This mechanism is generally observed only in applications such as die-attach of microwave power amplifiers and laser diodes. Although the absolute power levels are modest in these devices, the small physical size of the parts results in very high energy flux.

Pure indium

Pure indium is not often used as a solder because the wetting and spreading characteristics are mediocre, as are the mechanical properties of the joints. One exception stems from exploitation of the complex oxide that forms on indium. Very-high-purity indium is readily available because this metal is chemically extracted from zinc residues as a minor byproduct. Provided the indium is of purity better than 99.99995%, it will wet and spread over unmetallized oxide ceramics and glass, in air, without flux. The resulting joints do not have the same strength (5 to 10 MPa, or 725 to 1500 psi) and fracture toughness as conventional soldered joints, but are nevertheless hermetic and usable in a limited range of applications.

The low melting point of indium solders is caused by the low melting point of indium itself, which is 157°C (315°F). It is interesting to note that the cited melting point of indium has increased by nearly 5°C (9°F) over the last 40 years with the development of improved refining methods, as the melting point is very sensitive to low levels of metallic impurities. Albeit largely as a point of metallurgical curiosity, the melting point of indium is also unusually sensitive to pressure; the application of 4000 MPa (580 ksi) will cause the melting point to roughly double to 300°C (570°F), Fig. 5.

Alloying additions

Alloying additions made to form lower-melting-point eutectics confer a number of practical benefits**.** The table lists some of the more common indium solders and their melting points. The merits of alloying are principally the generation of multiphase microstructures, which improve the mechanical properties of the solder, and the formation of mixed-composition oxides, which are generally easier to chemically remove than pure indium oxide.

Indium oxide forms readily as a sticky and tenacious film that requires specially formulated fluxes to effect its removal. Even so, as can be seen from Fig. 6, indium solders are

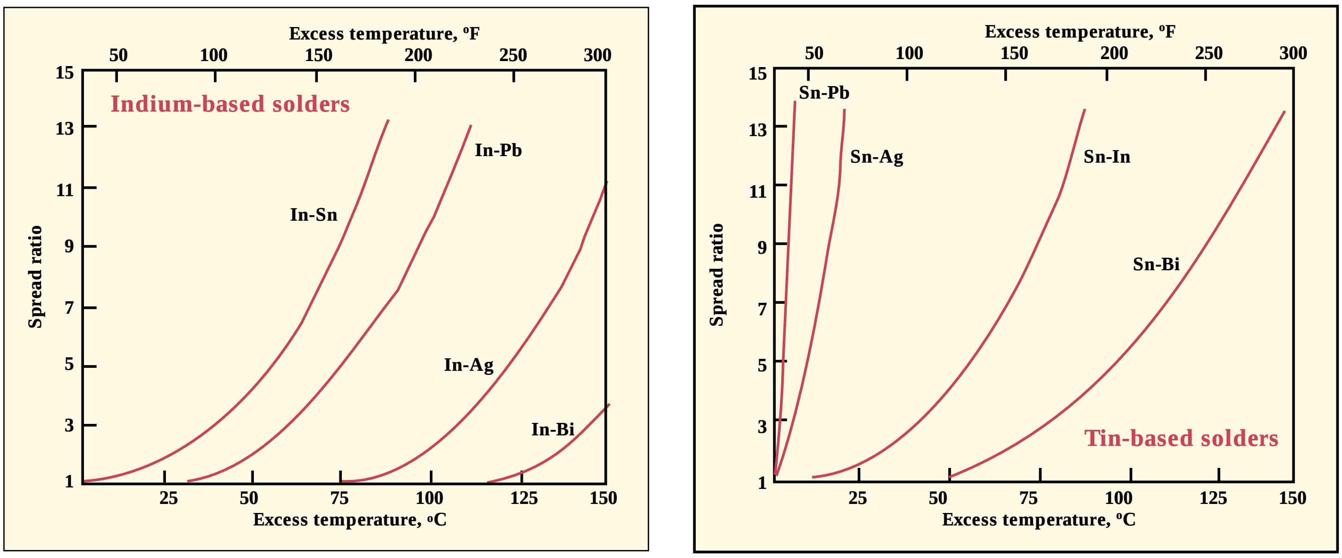

Fig. 6 — Spread characteristics of indium and tin binary alloys on an ideal substrate, as a function of excess temperature above the melting point. Indium solders are appreciably less fluid than their tin-base counterparts. The substrate is a flat microscope slide, sputter-metallized with 0.1 μm of chromium, overlaid with 0.1 μm of gold.

appreciably less fluid than their tin-base counterparts and require greater superheats to achieve comparable flow.

Indium-lead solders

Indium-lead alloys are a useful class of solders with readily adjustable melting ranges. Consideration of the phase diagram for this alloy system, which is given in Fig. 7, reveals that indium and lead form an essentially miscible mixture that extends between the melting points of the two parent materials, that is, 157 to 328°C (315 to 622°F). Thus, by appropriate selection of the composition, it is possible to obtain a solder, albeit one with a melting range and mediocre mechanical properties, that has any selected solidus temperature between the two limits.

Although indium-lead alloys solidify by peritectic reaction, the solidification rate of most soldered joints is usually sufficiently slow to prevent problems associated with microstructural coring, but this must be considered if a fast heating method such as laser soldering is needed.

Indium-containing solders are often recommended for joining to gold-coated components, because gold is less soluble in these alloys than in lead-tin solders. The restricted solubility of gold in a joint containing indium is largely associated with the formation of a continuous layer of the intermetallic compound $AuIn_2$ at the solder/gold interface.

This effectively suppresses further reaction between these metals.

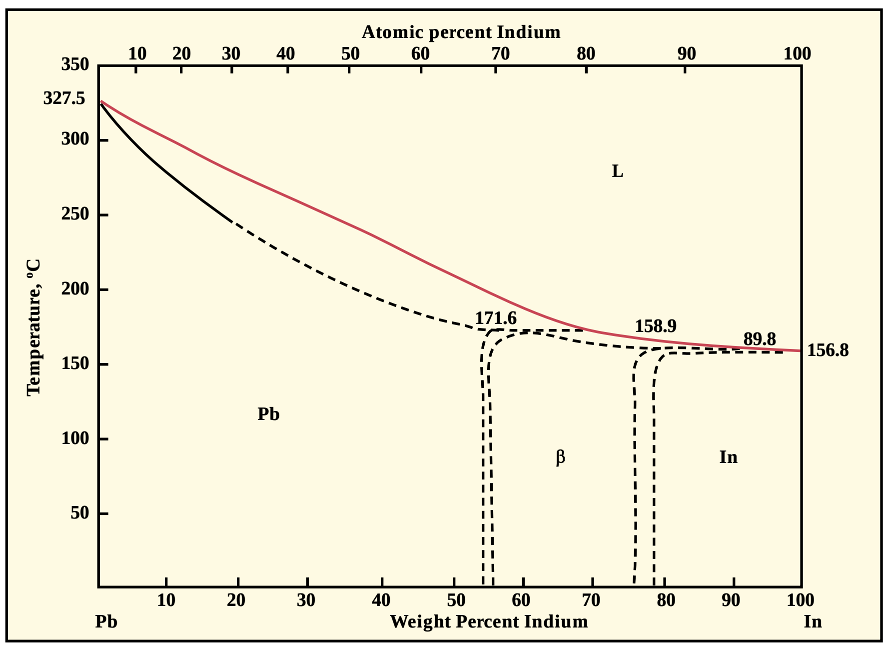

Fig. 7 — Indium-lead phase diagram. Indium and lead form an essentially miscible mixture that extends between the two melting points.

In the presence of lead, the interfacial layer takes the form of separate grains of the $AuIn_2$ compound embedded entirely in primary lead. The lead provides an easy diffusion path between the solder and the gold coating, and so permits the reaction to continue, although at a modest rate over extended timescales.

Intermediate melting temperature indium-base solders, such as the In-15Pb-5Ag composition, are significantly more ductile than lead-tin eutectic, and can yield joints with correspondingly superior thermal fatigue performance. Although the melting range of this alloy is close to the eutectic temperature of lead-tin solder, its price differential is a factor of about 80, which restricts its use to high-added-value and more specialist applications.

For more information: Giles Humpston, Tessera Inc., 3099 Orchard Drive, San Jose, CA 95134; tel: 408/894-0700; fax: 408/894-0768; e-mail: ghumpston@Tessera.com.

This article is based on parts of Chapter 2 in *Principles of Soldering*, by Giles Humpston and David M. Jacobson. Recently published by ASM International, the book is available online at www.asminternational.org, where you can view chapter titles. Or contact customer service at 800/336-5152. Price is $149 for ASM members, $182 for non-members.