Properties that are Important in Lead-Free Solders

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Abstract
The change to lead-free solders has forced the electronics industry to consider more than it ever has before what properties are important in a solder. When the tin-lead eutectic was the only solder considered in most applications it was a matter of adapting products and processes to the properties of that alloy, taking advantage of its strengths and designing around its weaknesses. With what seemed like an almost unlimited range of options the electronics industry faced a dilemma when it had to choose a lead-free solder to replace the tin-lead solder that it had relied on ever since there was an electronics industry. The initial concern was melting point as it was considered essential that the replacement alloy have a melting point as close as possible to the 183°C of the tin-lead eutectic. It has since been found that higher melting point alloys can be used without a *pro rata* increase in process temperature. The higher yield point of most lead-free solder options seemed initially to be a bonus but it has subsequently been realised that in some circumstances compliance is more important than strength. Although some properties of tin-lead solder have turned out to be not as essential in a lead-free solder as initially expected other properties are turning out to be as important in a lead-free as they were in tin-lead. Solidification behaviour and fluidity are two examples of such properties and it has been found that lead-free solders that match tin-lead solder in that regard offer measurable performance advantages. In this paper the authors will review the solder properties they consider important in a lead-free solder and report the results of measurement of these properties in a range of lead-free solders currently used or under consideration for commercial production.

Introduction
The vehemence of the opposition to the move to lead-free solder is an indication that is arguably the most disruptive change that has occurred in the field of electronics assembly. It is disruptive because it requires a major change in a fundamental element of an electronics assembly- the connections between components. Until they are connected the components that make up a functional circuit are nothing more than a collection of materials subassemblies that by themselves can do nothing. What bring that collection of components to life are the potential differences and the current flows that are possible only when they are joined by electrically and thermally conductive pathways. In most cases the material that provides those connections also provides the assembly with the mechanical integrity it requires to survive the stresses and strains of the environment in which it has to operate.

There have, of course, been concerns about other changes that have had implications for soldering technology. Even the very early step of incorporating flux into the solder wire used in hand soldering (rather than applying it separately) brought with it the challenge of completing a satisfactory solder joint with only the fixed amount of core flux in the length of solder wire required to form a fillet of the appropriate size. .

Wave soldering is now taken for granted and sometimes considered a rather low technology process but its successful implementation required that the industry look more seriously at the soldering process and the factors that affect it than it had previously. The individual attention that could be applied to a joint when it was hand soldered by a person with a soldering iron was no longer possible. The era of mass soldering had begun and if the process was to deliver the expected economic benefits an acceptable solder fillet had to be achieved on all joints in the few seconds that they were in contact with the molten solder. If there had to be a team of operators "touching up" the joints on the board as it exited the wave soldering machine then the process had failed. A case can be made that it was the introduction of wave soldering that forced the electronics assembly business to start treating soldering as science-based technology rather than an artisan skill.

One response to this challenge was the development of the concept of solderability. Solderability is a measure of the ease with which a joint substrate can be wetted by molten solder and it continues to an important consideration in all soldering processes, particularly as the industry moves to lead-free. The industry responded to the challenge of mass soldering processes with the development of solderable finishes for components and printed circuit boards, fluxes that had high activity without corrosive residues and wave soldering machines with heating systems and wave dynamics that facilitated the process of forming joints that complied with quality standards.

In the context of the subject matter of this paper, it is worth noting at this point that one of the particular responses to the introduction of wave soldering was a change in the composition of the solder used in this process from the 60/40 tin-lead that had been used since Roman times to 63/37 eutectic. Perhaps for the first time a rather esoteric metallurgical term, "eutectic", found its way into the vocabulary of electronics assembly.

The availability of cheap mass-produced electronics made possible by wave soldering was undoubtedly one of the factors that led to the massive expansion in the application of electronics to all aspects of modern life that in turn has driven the development of other soldering methods such as reflow soldering.

When the pressure to increase the density of electronic circuitry as well a reduce cost led to the introduction of surface mount technology the challenge was so great that the electronics industry responded with a collective effort to cope with the change. The organisations formed at that time have remained to help the industry deal with subsequent challenges and are now active in helping the industry in its adoption of lead-free soldering. The introduction of a new soldering material, solder paste, required that those with the responsibility of managing electronics assembly had to cope with new concepts such as viscosity and thixotropic index, tackiness and open time. Machine makers were judged by the ΔT their ovens could deliver.

These foregoing changes were driven purely by technical/economic considerations. The Montreal Protocol provided the electronics industry with its first experience of a change that was driven by a concern about the environment. The fairly simple cleaning processes made possible by the great dissolving power of the chlorofluorinated hydrocarbons that the industry was forced to give up had made it possible to use high activity high solids fluxes that provided a wide process window. Cleaning processes that match the effectiveness of the CFC solvents have subsequently been developed but the first response was to develop new flux technologies and improve the solderability of joint substrates so that reliable soldering could be effected with minimal, safe residues that did not need cleaning.

It has to be acknowledged, however, that all of the foregoing changes were made without changing the basic metallurgy of the alloy used in printed board assembly which was rooted firmly in the tin-lead alloy system with usually never less than 36% lead (Figure 1).

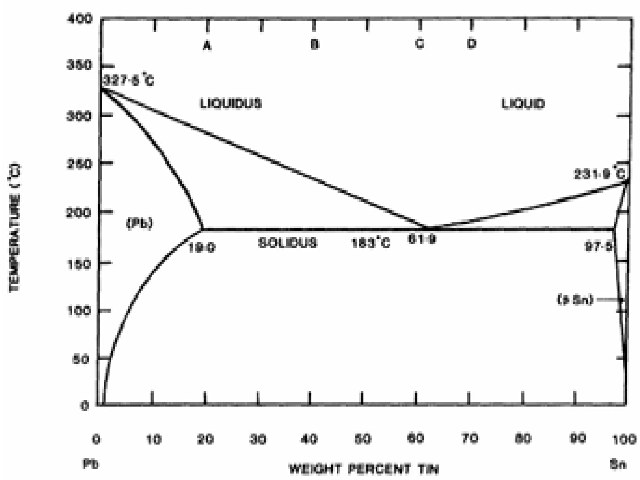

Figure 1- The Tin-lead system provides the benchmark for lead-free solders

Sometimes advantage was taken of the steeply rising solidus line at the lead-rich end of the system to make a high melting point solder which was useful in component manufacture. Sometimes up to 2% silver or 2% copper was added either to suppress erosion of those elements from substrates or soldering tools or to strengthen the solder by the introduction of an intermetallic phase to the microstructure. However, the properties of the solder were determined primarily by the fact that the alloy consisted of two metallic phases, tin with up to around 2 % lead in solid solution and lead with up to about 20% tin in solid solution. And in the eutectic alloy, nominally Sn-37Pb these two metallic phases are present in the form of a fine lamella structure of interleaved layers (Figure 2)

Benchmarking Against Tin-Lead Solder

Whether the tin-lead eutectic really is the best alloy for soldering electronic assemblies or whether it is just that electronic circuit design and electronics assembly processes developed within the constraints of its limitations this alloy has to be considered the benchmark against which candidate lead-free solders can be judged.

When there was no reason to consider alternatives tin-lead solder was so taken for granted that its properties have not always been recognised, even by those who are now so keen to keep on using it.

The only things that most lead-free solders have in common with tin-lead solders is that tin is the major ingredient and that they work by establishing a metallurgical bond with the substrate by reacting to form an intermetallic compound with the substrate metals. The differences in the fundamental metallurgy of tin-lead and lead-free solders are greater than the similarities.

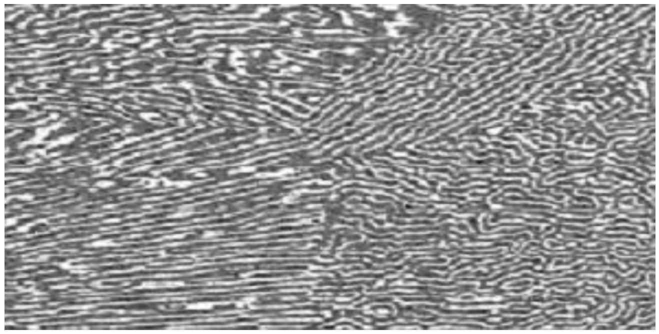

Figure 2- The microstructure of the tin-lead eutectic

Solder Properties

The properties of solders can be considered to fall into two categories, those that affect their performance in soldering processes and those that affect the reliability in service of solder joints made with them.

Included on the first category are

- Melting point
- Wetting properties
- Fluidity
- Aggressiveness towards copper
- Aggressiveness towards soldering equipment
- Stability in the molten alloy

In the second category are

- Strength and ductility
- Impact strength
- Microstructure
- Stability of microstructure/ Intermetallic growth
- Reliability

Melting Point

While in the early days of lead-free alloy development one of the primary objectives was getting a melting point as close as possible to that of Sn-37Pb it was found subsequently that less superheat (the extent to which the process temperature exceeds the melting point) is required with lead-free solders than with tin-lead solder (Table 1). It was realised that the superheat in the tin-lead process was largely to get the joint to wetting temperature and preheat could achieve a similar effect. The temperature that it is necessary to reach to form a joint seems to be much the same for lead-free solders as tin-lead solder and this is probably related to the fact that in both cases the wetting reaction is the same; the joint achieves metallurgical integrity when the tin in the solder reacts with the substrate metal to form an interfacial intermetallic.

Table 1- Typical soldering process temperatures

Alloy System	Melting Point	Typical Process Temperatures (°C)		
		Wire	Wave	Reflow
		Tip Temperature	Solder Temperature	Peak Temperature
Sn-Cu	227°C	330-380	255-270	230-255
Sn-Ag-Cu	217°C	330-380	255-270	240-255
Sn-Pb	183°C	330-380	245-260	205-220

An inference from this observation is that if it has other useful properties an alloy need not be eliminated from consideration because of a melting point that is higher but still within a range those components and circuit materials can tolerate.

Wetting Properties
The standard wetting balance test can give a misleading impression of the effectiveness of an alloy to the extent that the wetting time includes the time taken to get the test piece to the melting point of the solder as well as the time that it takes for the solder to wet the substrate to the maximum extent. An alloy with a higher melting point can actually wet faster than one with a lower melting point. In Figure 3 it can be seen that it takes a little longer for the test piece to get to the melting point of the SnCuNiGe but that alloy then wets it at a rate faster than that than of the lower melting point SnAgCu alloy. In practical soldering a difference in melting point can be compensated for by adjustments to other process parameters such as preheat. The more important property of the solder is its wetting rate.

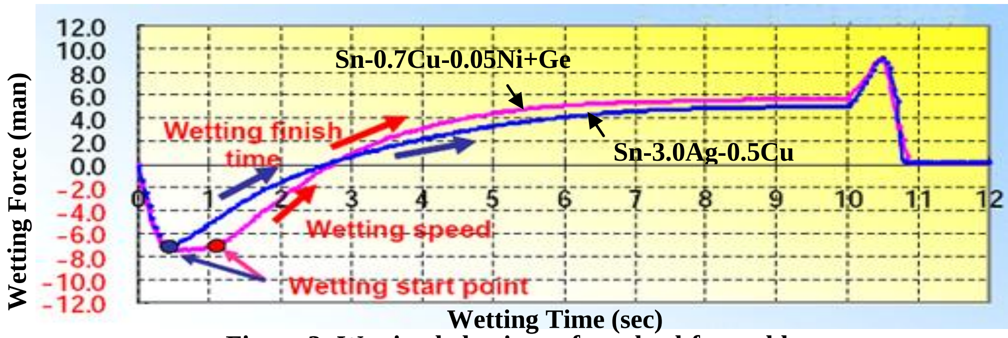

Figure 3- Wetting behaviour of two lead-free solders

Fluidity
All soldering processes rely on the flow of solder into the joint. That process is driven by the capillary forces resulting from the wetting of the joint substrates but a property of molten metals known in the foundry industry as "fluidity" is also important. Like metal casting soldering relies on the flow of a molten metal that is close to its melting point to form the fillet and in wave soldering fluidity is also important in the drainage of excess solder that would otherwise cause shorts. A method developed by the foundry industry (Figure 4) has been found to be useful in measuring the fluidity of solder alloy.

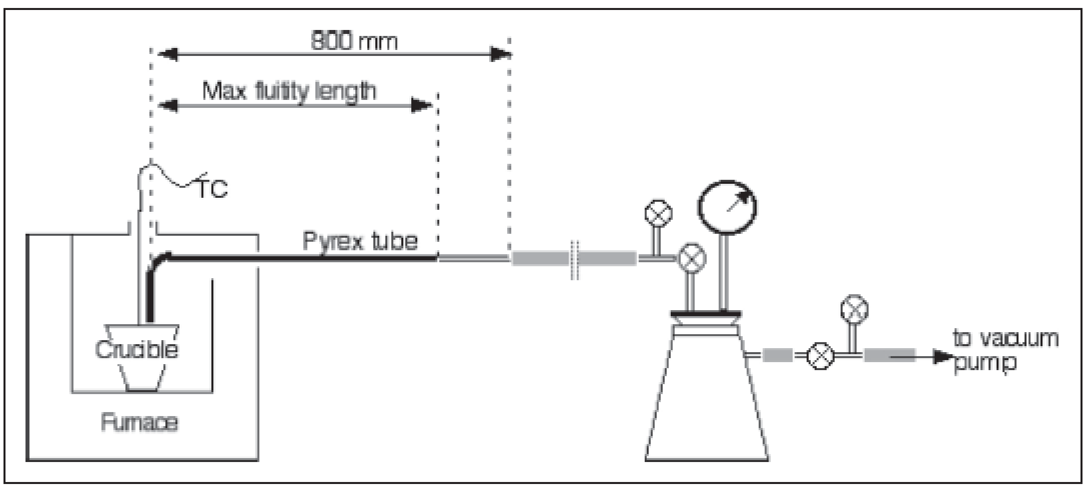

Figure 4- The Ragone method of measuring the fluidity of solder alloys.

The significance of this property can be inferred from the fact that in the tin-lead alloy system fluidity is at its peak at the eutectic composition towards which the electronics industry migrated as the challenges that soldering processes had to deal with increased (Figure 5).

Testing of lead-free solders currently being offered to the electronics industry indicate that fluidity measured at 40°C above liquidus ranges from close to that of the tin-lead eutectic to 30% lower (Figure 6).

The negative effect of silver additions on the fluidity of the SnCuNi alloy is illustrated in Figure 7.

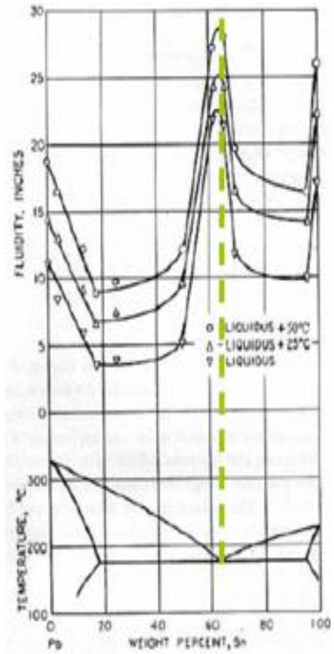

Figure 5- Fluidity peaks in the Sn-Pb system at the eutectic composition

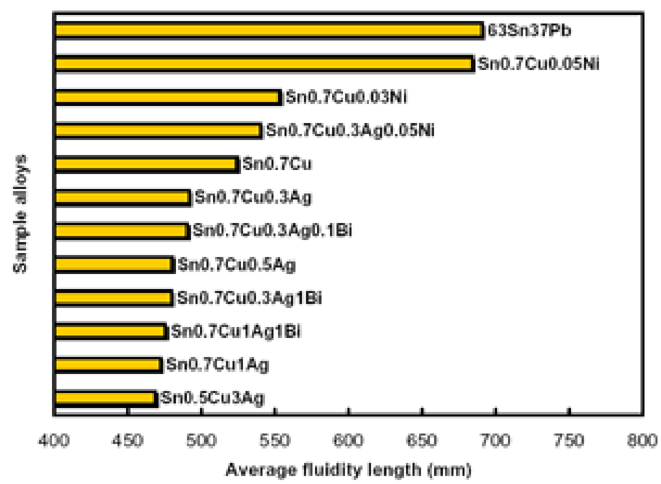

Figure 6- Fluidity of some lead-free solder compared with that of tin-lead eutectic

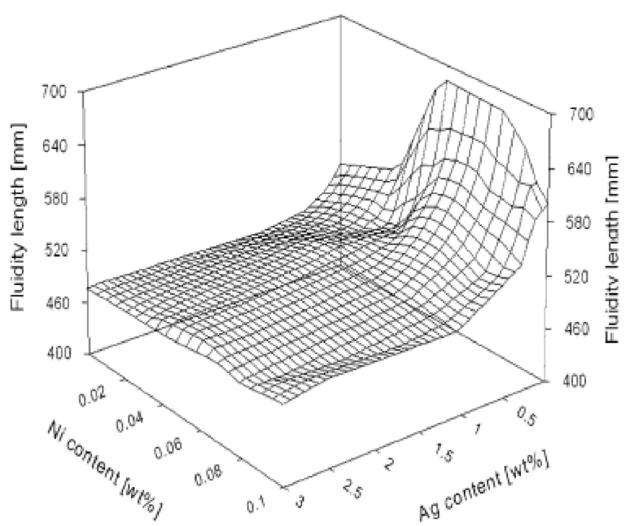

Figure 7- Fluidity of tin-copper based solder as a function of nickel and silver levels

Aggressiveness towards Copper
One of the unanticipated issues to emerge in the early stages of the implementation of lead-free soldering was the erosion of copper substrates. In Figure 8 the solder flow is from left to right.

Molten tin is quite aggressive towards most metals eroding them quite quickly. That aggressiveness is substantially reduced when the tin is diluted with lead so that dissolution of copper substrates by eutectic tin-lead solder has not been a major problem. Without that moderating influence lead-free solders tend to erode copper substrates so rapidly that the integrity of a solder joint to the copper foil of a printed circuit boards can be compromised.

There are significant differences between the rates at which lead-free solders erode copper (Figure 9).

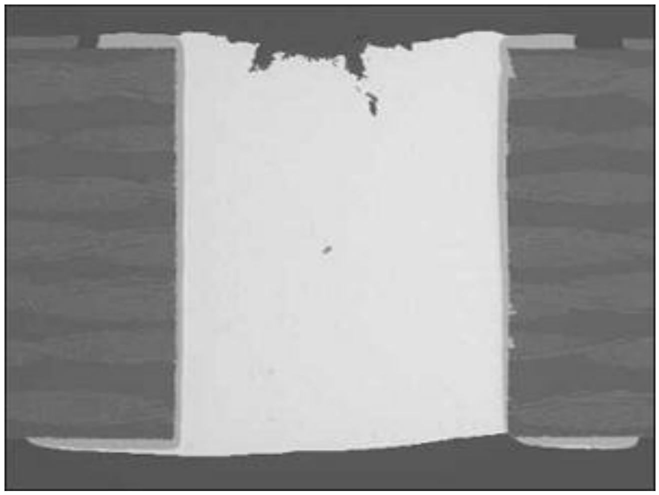

Figure 8- Erosion of through hole copper by lead-free sold

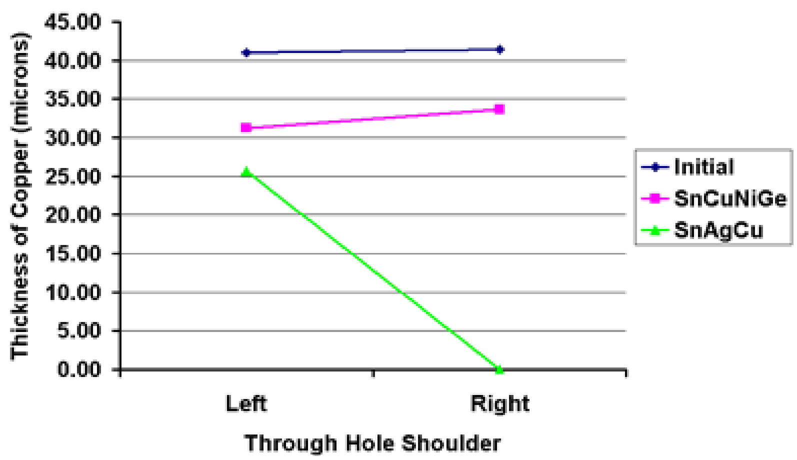

Figure 9- Copper erosion by lead-free solders.

Aggressiveness toward Soldering Equipment
Probably because of an interaction between silver oxide and the nickel and chromium oxides that make stainless steel "stainless" lead-free solders that contain silver, even at low levels, tend to erode soldering equipment. That tendency is exacerbated by the phosphorus that is usually also added to silver-containing lead-free solders to manage the high dross rate of these alloys. The erosion of the wave former in Figure 10 occurred in less than a year's normal operation with a low-silver SAC alloy.

The erosion problem can be managed by the use of special materials, coatings and surface treatments but this add cost and does not necessarily provide a permanent solution. Silver-free solders with alternative anti-drossing additions can be used safely with plain stainless steel equipment.

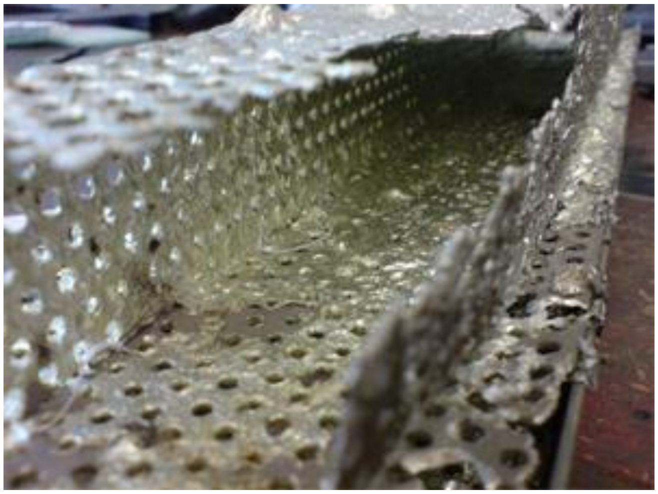
Figure 10- Erosion of soldering machine parts by low SAC solder

Stability of Molten Solder

The new generation of "microalloyed" solder based around the tin-copper eutectic rely on additions of high melting point elements such as nickel and cobalt. For stable long term operation in solder baths it is essential that high melting point intermetallic phases do not form in the working solder bath if consistent soldering performance is to be maintained. The cubic cobalt-tin intermetallic that is stable at soldering temperatures settles out of the melt so that the microalloying addition is not available to modify the alloy behaviour as intended (Figure 11)

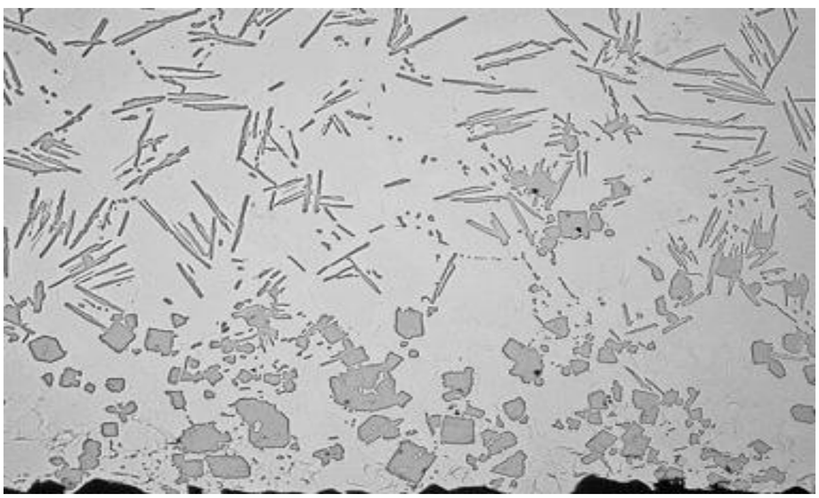
Figure 11- Segregation of CoSn intermetallic in working solder bath

Strength and Ductility

While tin-lead solder is a mixture of tin and lead metallic phases that are soft the intermetallic phases in lead-free solders are hard. Depending on their morphology and distribution the intermetallic phases can increase the yield strength of the solder. While the combination of intermetallics in SnAgCu alloys increase strength they also reduce ductility (Table 2). While in some cases that higher strength is an advantage, the associated brittleness is the cause of many of the reliability problems that are being encountered with lead-free solders. One of the under-appreciated advantages of tin-lead solder was its ductility, i.e. its ability to absorb substantial strain without work hardening and cracking. The wide range of materials with different coefficients of thermal expansion that are used in the construction of electronics assemblies means that there is substantial relative movement within the assembly. As the materials that hold these assemblies of different materials together the solder joints have to accommodate those strains. If the strain can be taken up by flexing of circuit elements such as component leads then the high yield point of some lead-free solders can mean a long service life for the solder. However, if the solder itself has to accommodate the strain then the rapid work hardening that occurs can result in early cracking and joint failure. Lead-free solders that do not contain silver have a lower strength but their higher ductility means that they can accommodate more strain without cracking. The analysis of reliability data summarised in Figure 12 (1) confirms the benefit of alloy ductility when the solder joint is subjected to large accumulated strain.

Table 2- Basic mechanical properties of some solder alloys

Alloy	Tensile Strength (MPa)	Elongation %
SnPb	44	25
SnCuNiGe	32	48
SnAgCu	52	27

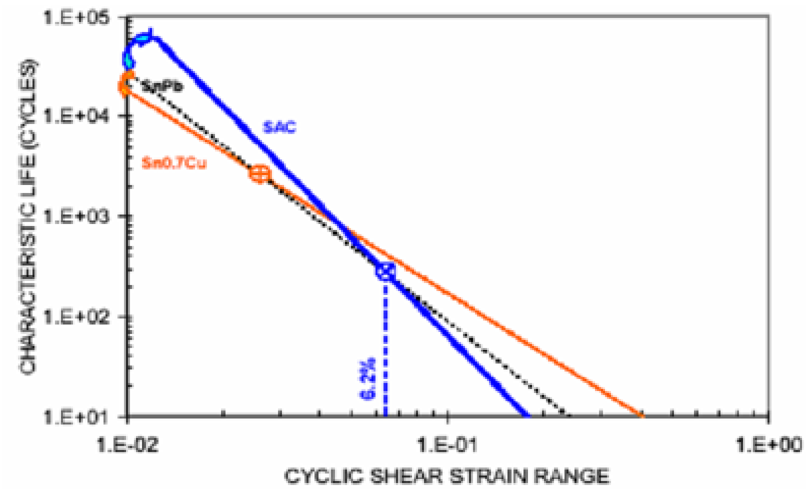

Figure 12- Solder joint life as a function of accumulated shear strain

Impact Strength

The use of electronics in portable devices that can be dropped has increased the likelihood of solder joints being subjected to impact loading. Testing of BGA at shear speeds of up to 4000mm/sec reveals differences between lead-free solders in the sensitivity of their strength and fracture energy to shear speed (Figure 13). The tendency to low energy (brittle) fracture at high shear speeds in SnAgCu alloy is a consequence of brittle interfacial intermetallic and the high strain rate sensitivity of shear stress of the bulk alloy.

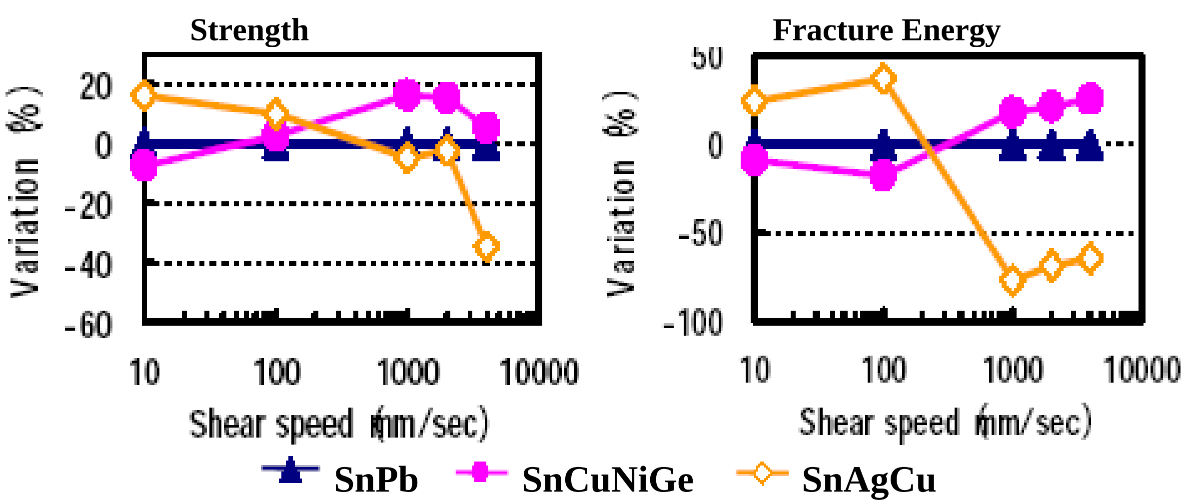

Figure 13- Impact strength of lead-free BGA compared to SnPb BGA as a function of shear speed.

Stability of Microstructure/Intermetallic Growth

While there was seldom a need to consider the microstructure of tin-lead solder the microstructure of lead-free solders is an important consideration in their performance in soldering processes and their reliability in service.

If the only alloying additions are silver and/or copper then the matrix is nearly pure tin with the alloying additions present only in the form of intermetallic compounds with tin, Ag_3Sn and Cu_6Sn_5. While both phases in tin-lead solder are soft, ductile and metallic in character with a non-faceted morphology the intermetallic compounds in lead-free solders are hard, brittle and non-metallic in character. If the composition and cooling conditions favour their growth as the first phase then the intermetallic compounds have a distinctive faceted morphology (Figure 14). Ag_3Sn crystals take the form of flat plates while Cu_6Sn_5 usually occurs as hexagonal prisms that are sometimes hollow.

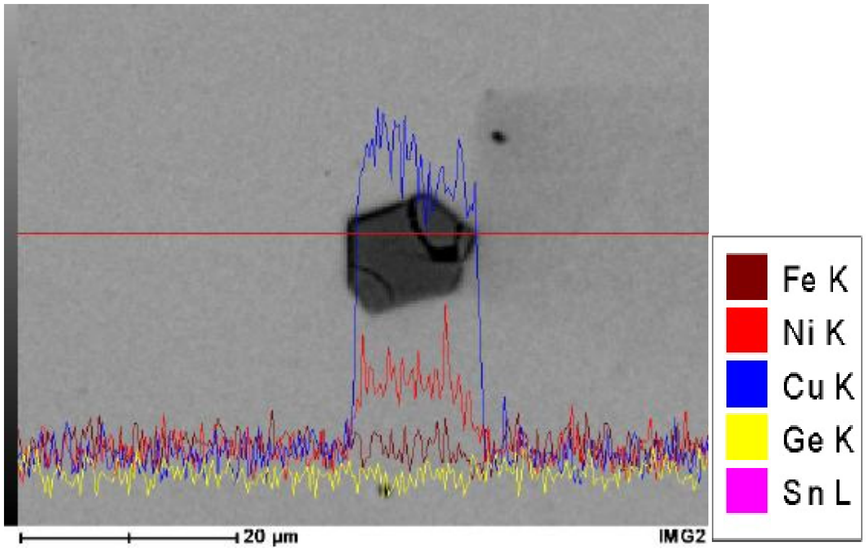

Figure 14- Faceted morphology of $(Cu,Ni)_6Sn_5$ crystal in SnCuNiGe alloy

Even if the composition is nominally eutectic, such as the Sn-3.8Ag-0.7Cu alloy, unless the alloy has been modified by a further addition the difficulty of nucleating the intermetallic phases means that the alloy can cool to nearly 20°C below its nominal melting point before solidification begins. This undercooling favours the growth of tin dendrites that can take up a major part of the microstructure before the resulting concentration of solute elements begins to favour solidification as a pseudobinary or ternary eutectic with the characteristic fine dispersion of phases (Figure 15).

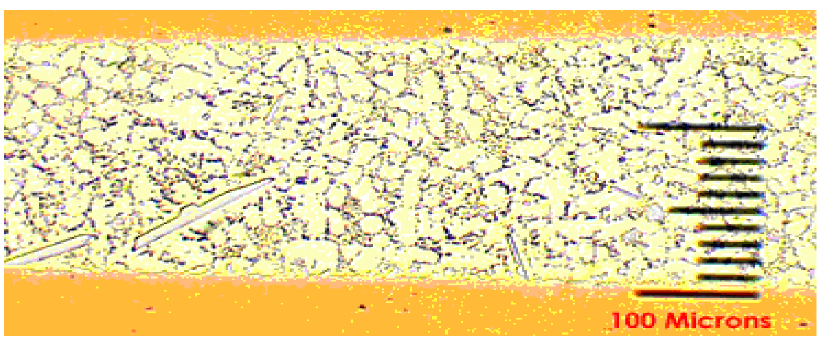

Figure 15- Sn dendrites and Ag_3Sn plates that dominate the SnAgCu alloy microstructure

On the basis that the fine microstructure of the tin-lead eutectic (Figure 2) free of primary tin dendrites is a desirable feature in a solder the fine dispersed microstructure that can be obtained by ternary additions to the tin-copper eutectic (Figure 16) would be expected to enhance the properties of the alloy and there is some qualitative evidence to support that position

Stability of Microstructural / Intermetallic Growth

The fine eutectic structure of tin-lead solder coarsens as the solder is aged at elevated temperature (Figure 17). And while there is some reaction between the tin and a copper substrate the rate of reaction is slowed by the dilution with lead and there is no other element playing a role in the process. The intermetallic phases in lead-free solders are more stable but the high tin content means that there is a tendency to more intermetallic growth at the interface (Figure 17).

While silver seems to accelerate growth of the interfacial intermetallic nickel has been found to inhibit the growth of that intermetallic in the tin-copper eutectic system (Figure 18). Although initially thicker the intermetallic in the SnCuNi system grows more slowly than that in other alloy systems. The stability of the intermetallic is expected to have beneficial consequences for the reliability of this alloy in service.

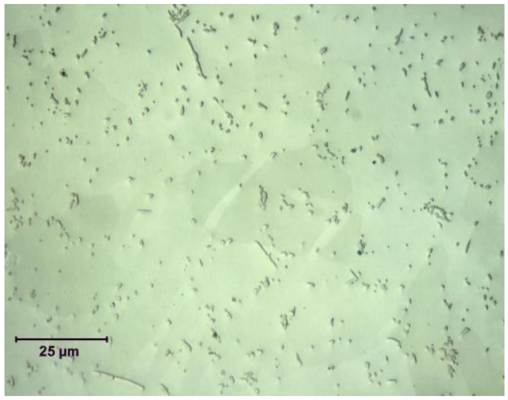

Figure 16- Fine dispersed intermetallic phase in nickel-modified tin-copper eutectic

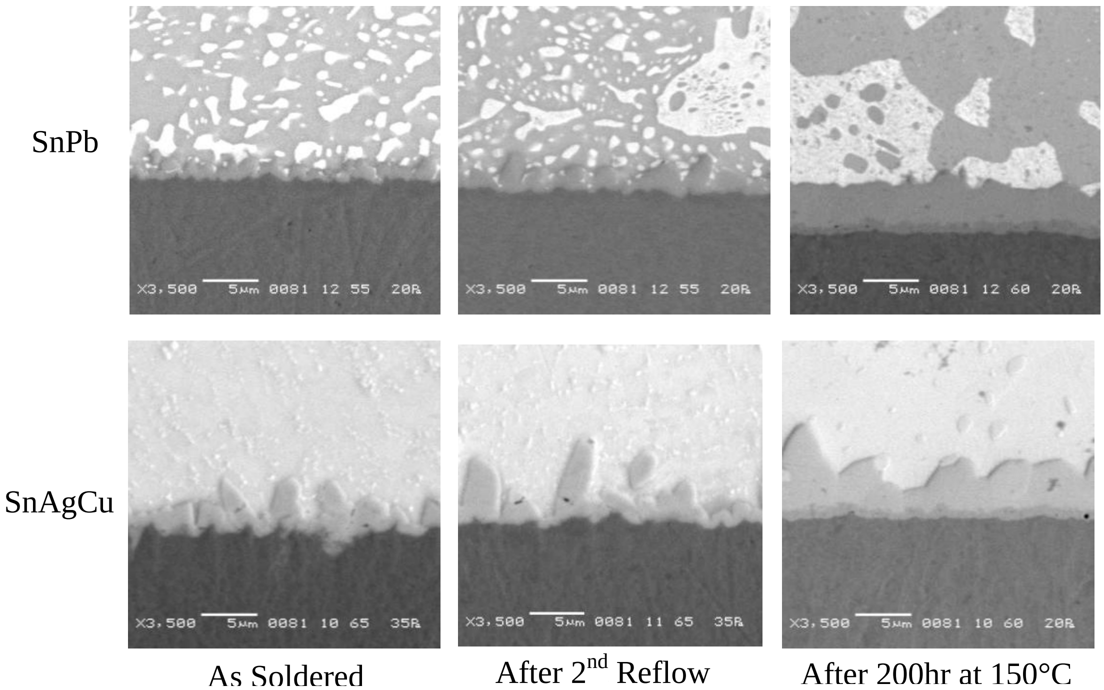

Figure 17- Microstructural change at elevated temperature

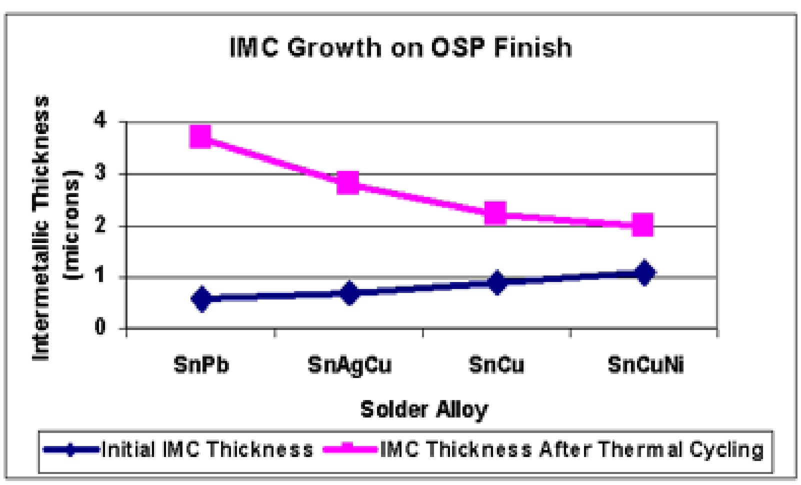

Figure 18- Intermetallic growth after 4000 cycles -40 - +125°C

Reliability

Reliability is a complex phenomenon about which it is dangerous to generalise. Figure 19 which compares the performance of Sn-3.0Ag-0.5Cu and Sn-0.7Cu-0.06Ni+Ge with Sn-37Pb in 30G vibration and Figure 20 which compares the performance of this alloys in thermal cycling suggest that the SnCuNi alloy is closer in reliability performance to SnPb. That is consistent with its mechanical properties and microstructure considered earlier.

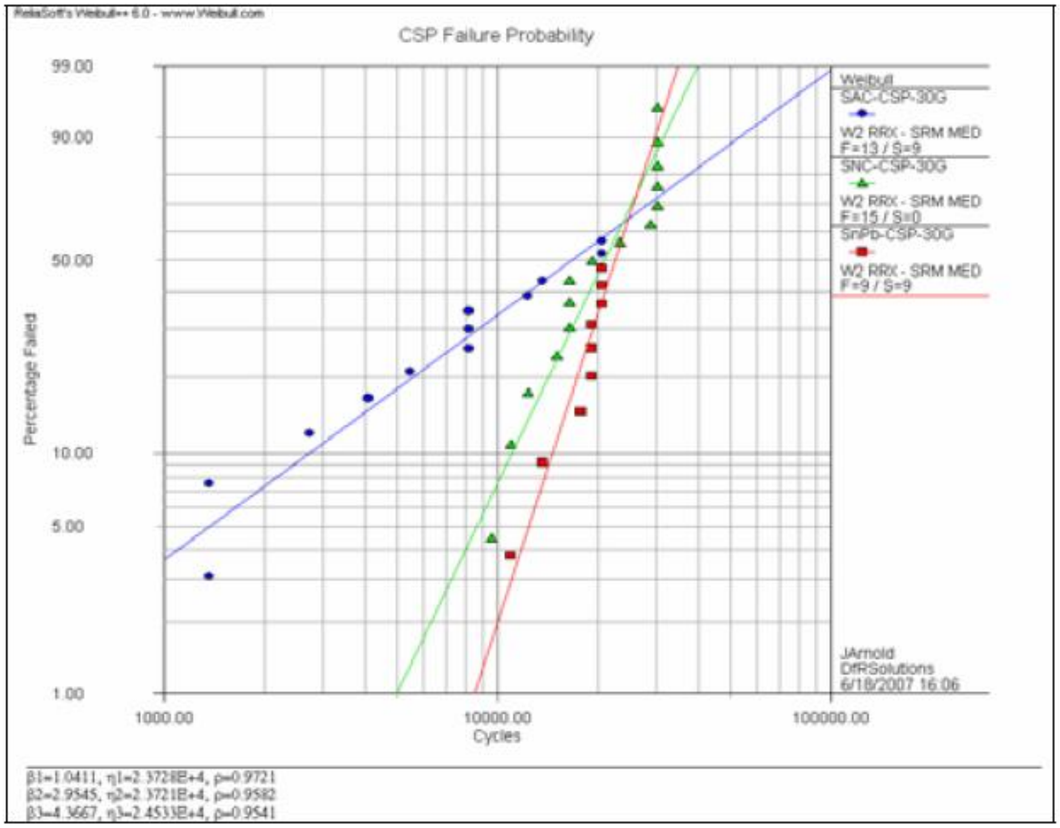

Figure 19- Comparison of lead-free solders with tin-lead in vibration testing at 30G

Choosing a Lead-Free Solder

The following considerations emerge from the first eight years of commercial mass production with lead-free solders and the testing and development that has been done to support this change in one of key materials of electronics assembly.

For applications where a solder joint is likely to be subjected to substantial accumulated strain or impact loading choose a solder with good ductility and a stable interfacial intermetallic. Where the joint experiences Joule heating from carrying high currents the stability of the intermetallic at the interface and in the body of the solder has been found to be particularly important.

Fluidity is a property that affects the performance of a solder in all applications and is a valid selection criterion. Fluidity is associated with a eutectic mode of solidification and the resultant fine uniform structure largely free of primary tin dendrites seems to be beneficial to the performance of an alloy as a solder.

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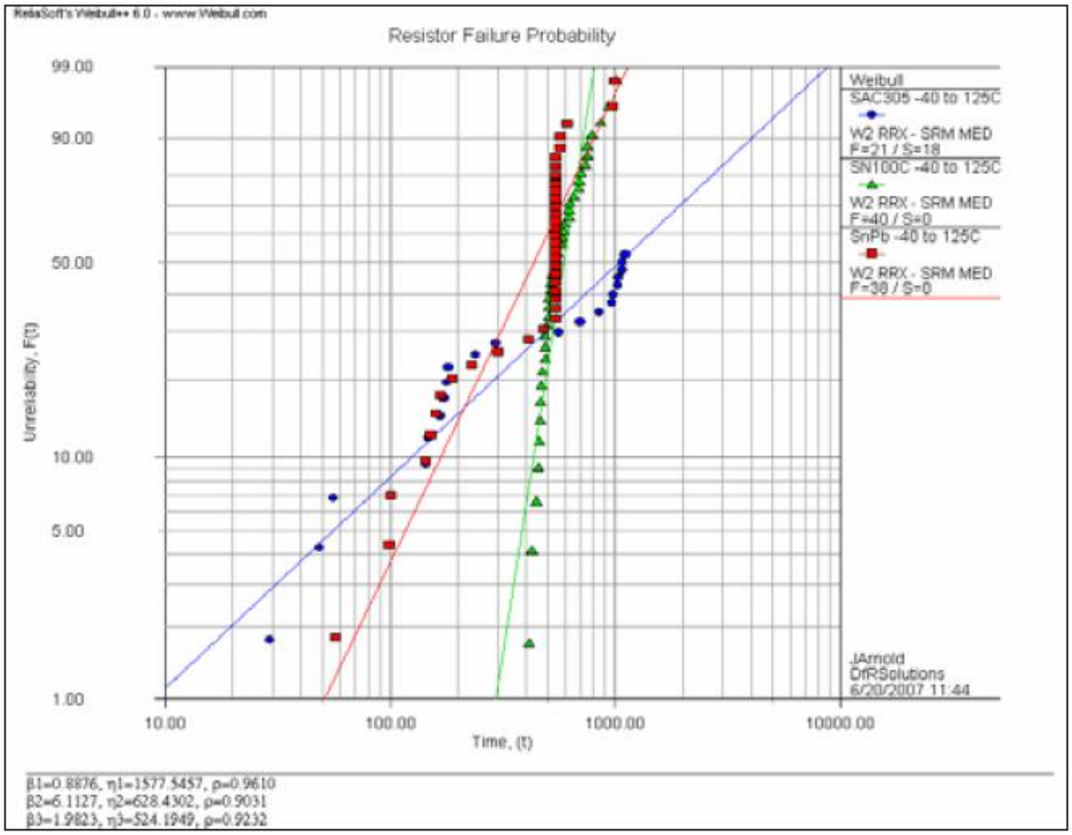

Figure 20- Comparison of lead-free solders with tin-lead in thermal cycling of CSP -40-125°C

Reference

(1) J-P Clech, "Lead-Free and Mixed Assembly Solder Joint- Reliability Trends"- IPC Printed Circuits Expo SMEMA Council APEX Designer Summit 2004

Properties that are Important in a Lead-free Solder

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your partner for soldering solution

NIHON SUPERIOR

OBJECTIVE

To provide a framework in which candidate lead-free solders can be assessed for the suitability as replacements for Sn-37Pb

Properties that Affect
<u>Performance in Soldering Processes</u>

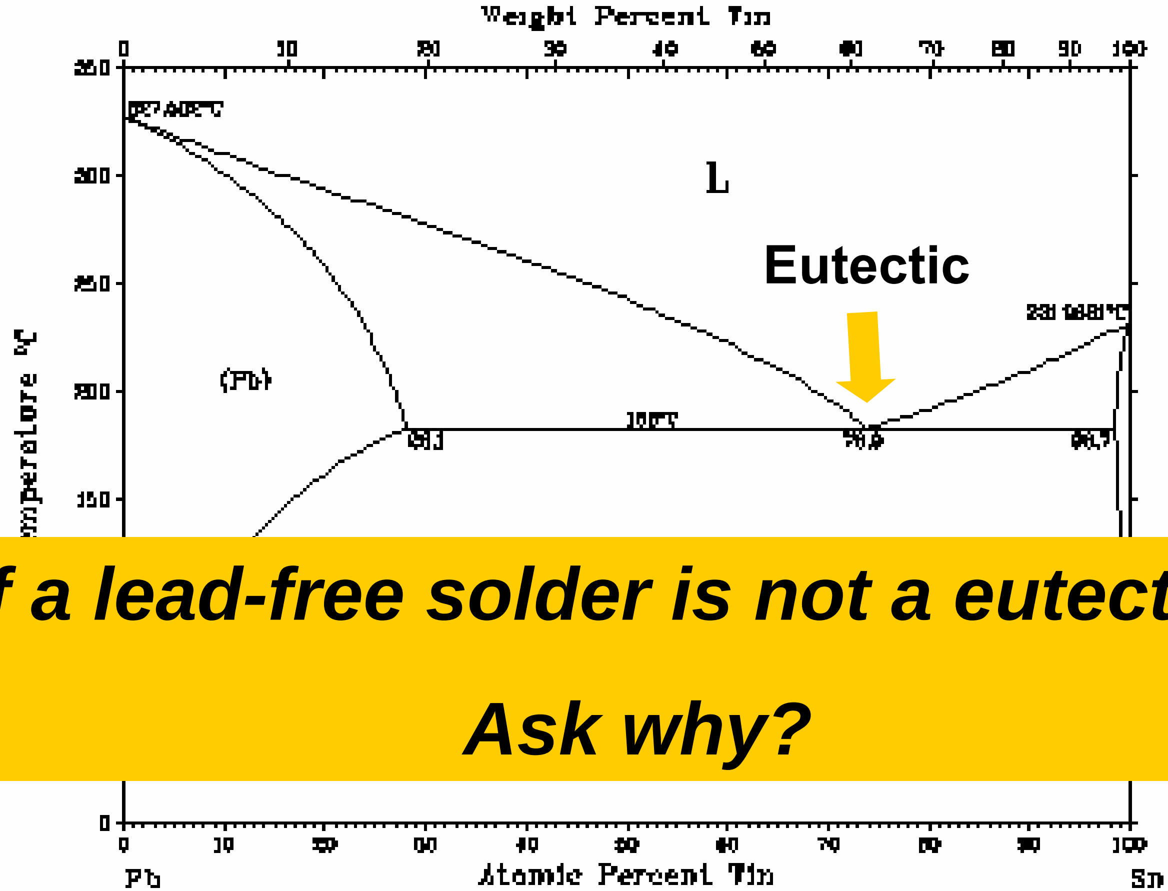
- **Melting point**
- **Wetting properties**
- **Solidification mode/Fluidity/Drainage**
- **Aggressiveness towards copper**
- **Aggressiveness towards soldering equipment**
- **Stability of the molten alloy**

Properties that Affect
<u>Performance in Service</u>

- **Strength and ductility**
- **Impact strength**
- **Microstructure**
- **Stability of microstructure/ Intermetallic growth**
- **Reliability**

Selecting Lead-Free Alloy Systems?

What can we learn from tin-lead solder?

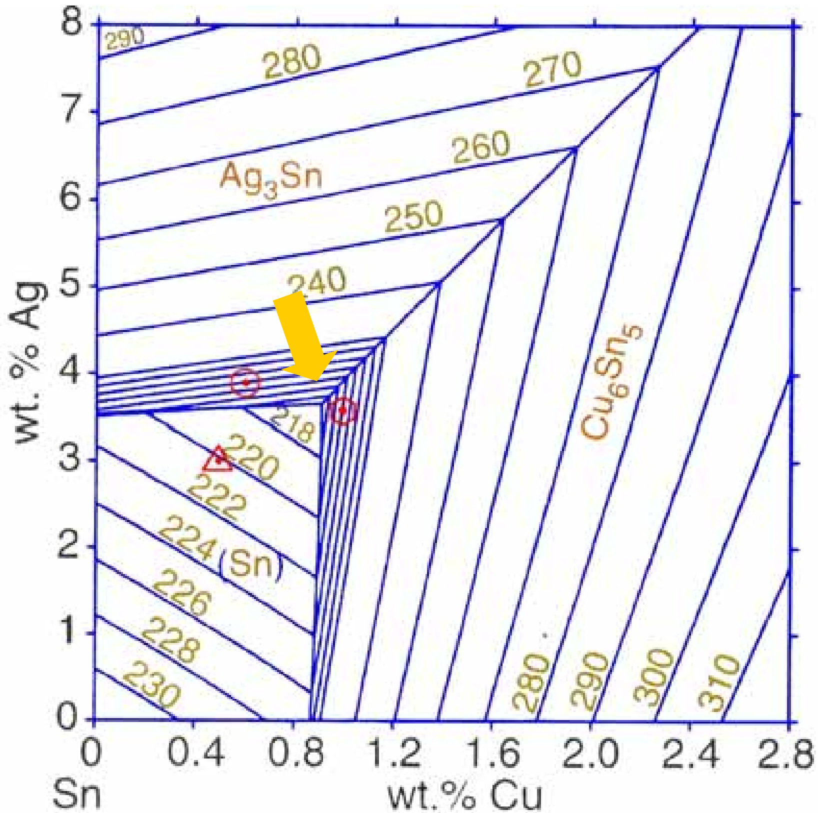


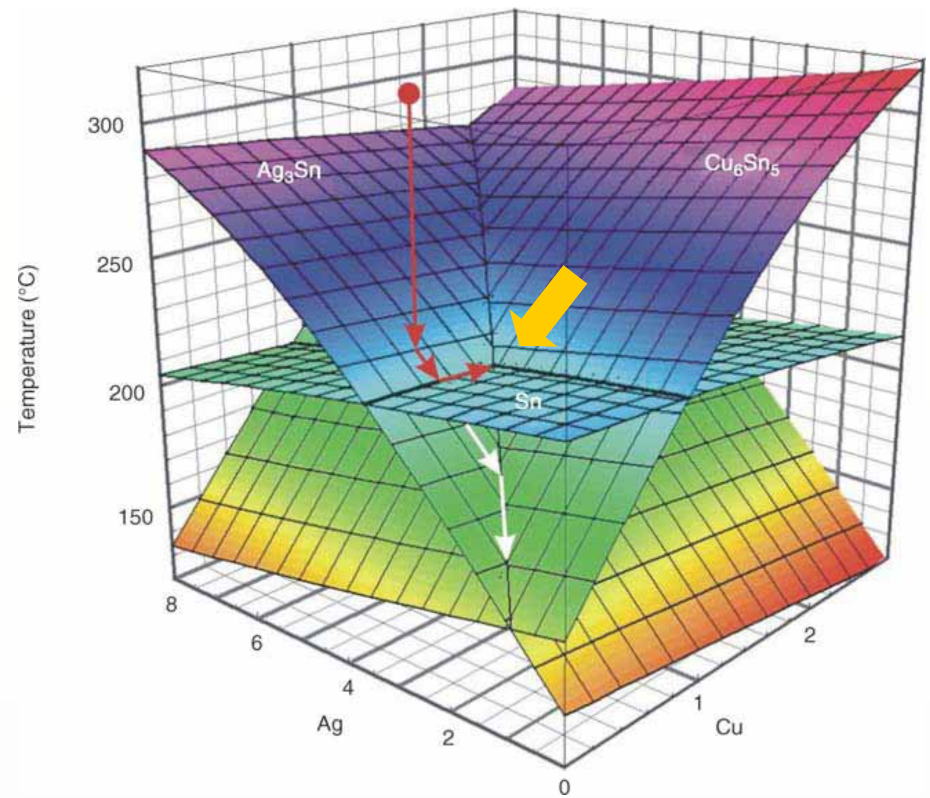
If a lead-free solder is not a eutectic…

Ask why?

Lead-Free Alloy Systems

1. Alloys based around the Sn-Ag-Cu Eutectic ★

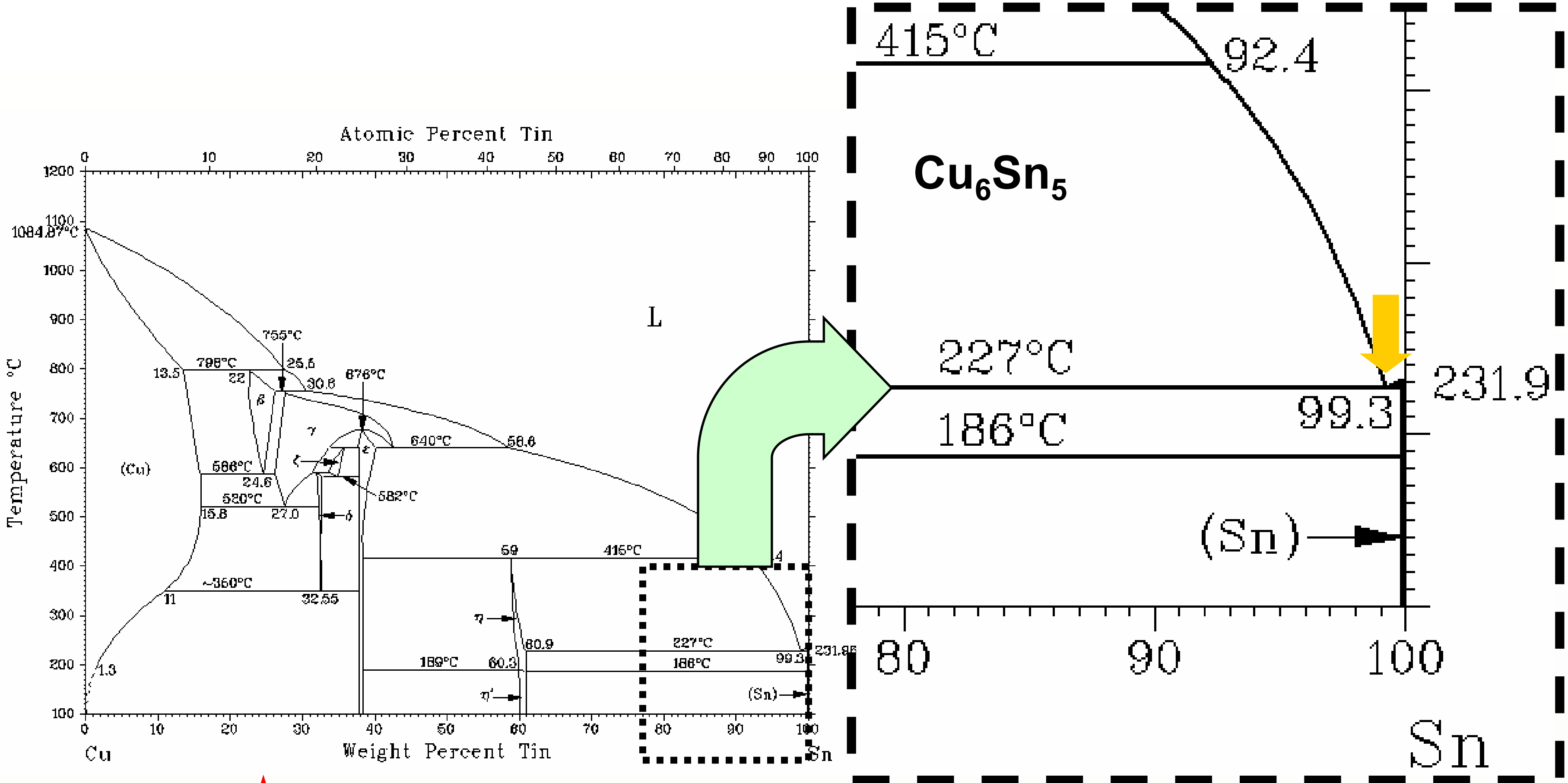




★ *But not necessarily eutectic or behaving as a eutectic*

Lead-Free Alloy Systems

2. Alloys based around the Sn-Cu Eutectic★



★ *But not necessarily eutectic or behaving as a eutectic*

Selecting Lead-Free Alloy Systems?

Environmental Impact

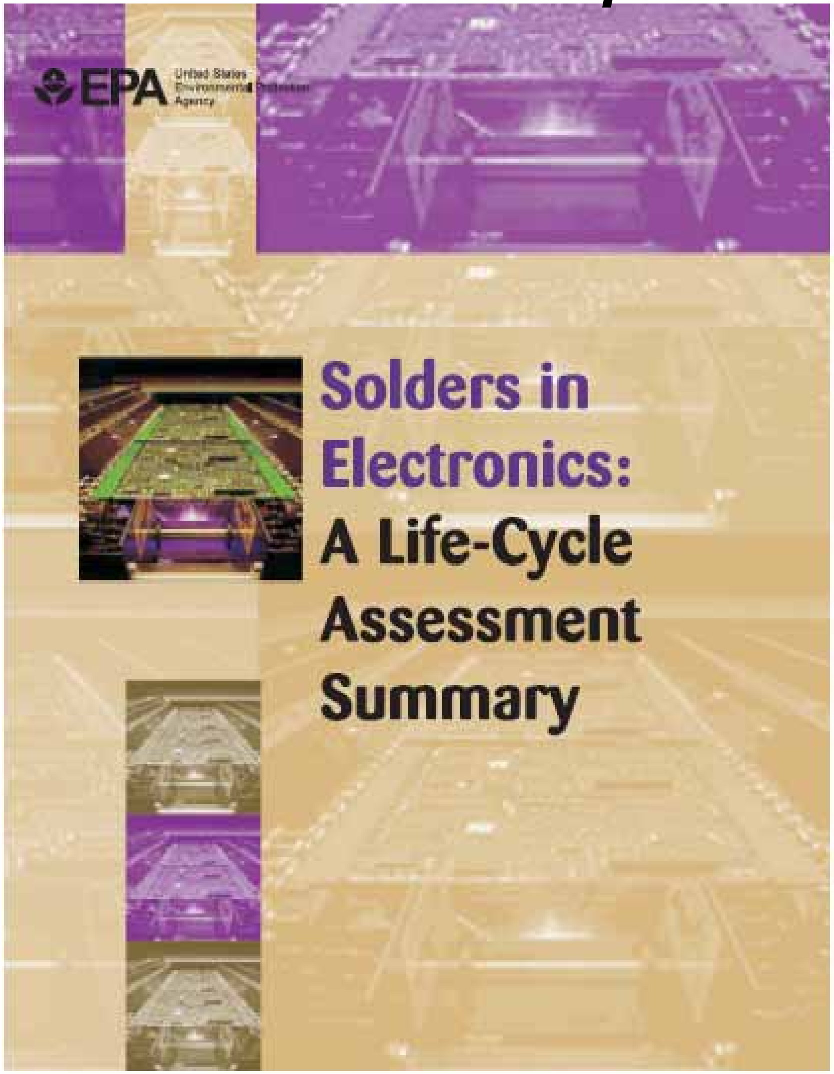
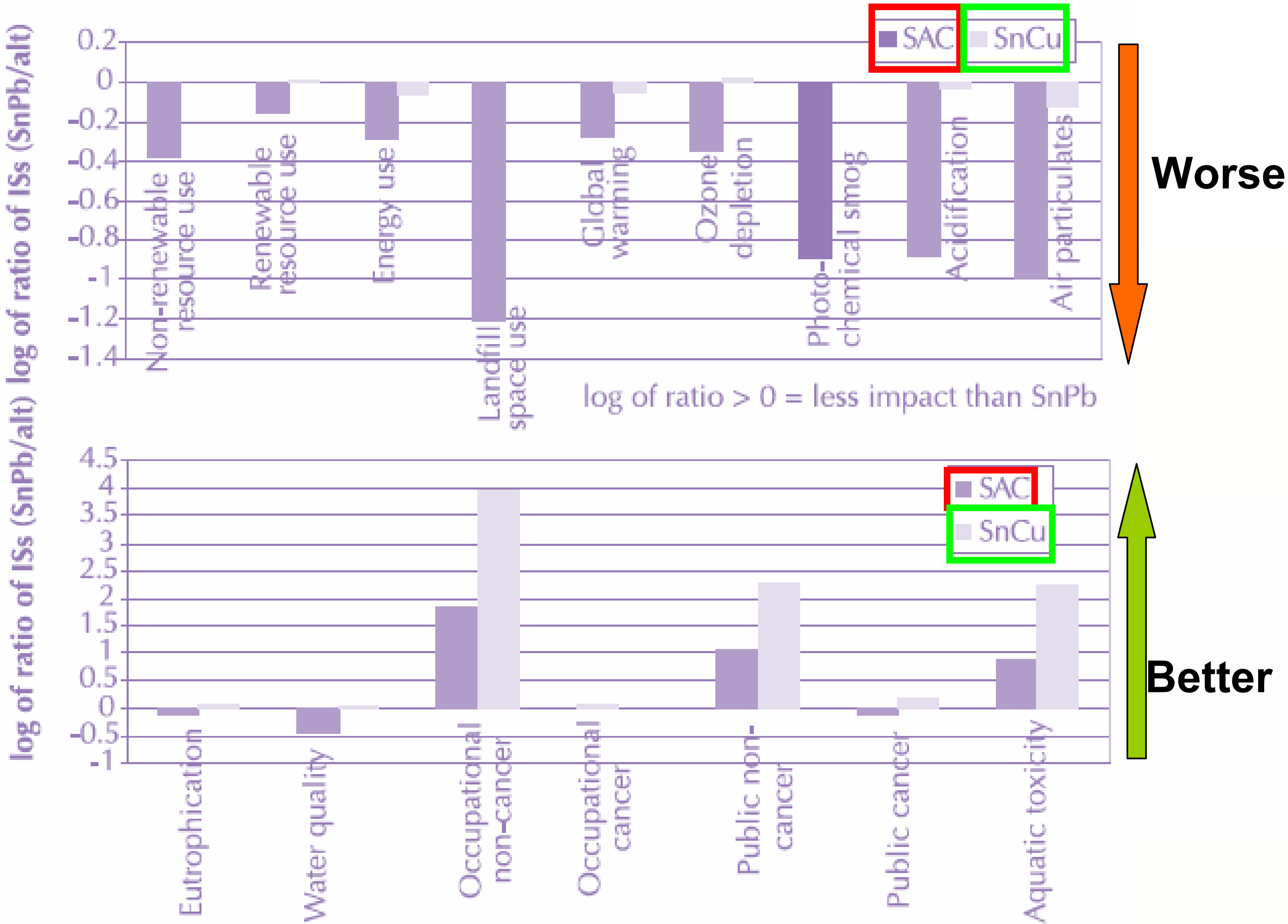


Figure 5.1. Relative Comparison of Bar Solder Life-Cycle Impact Scores



Properties that Affect Performance in Soldering Processes

Melting Point

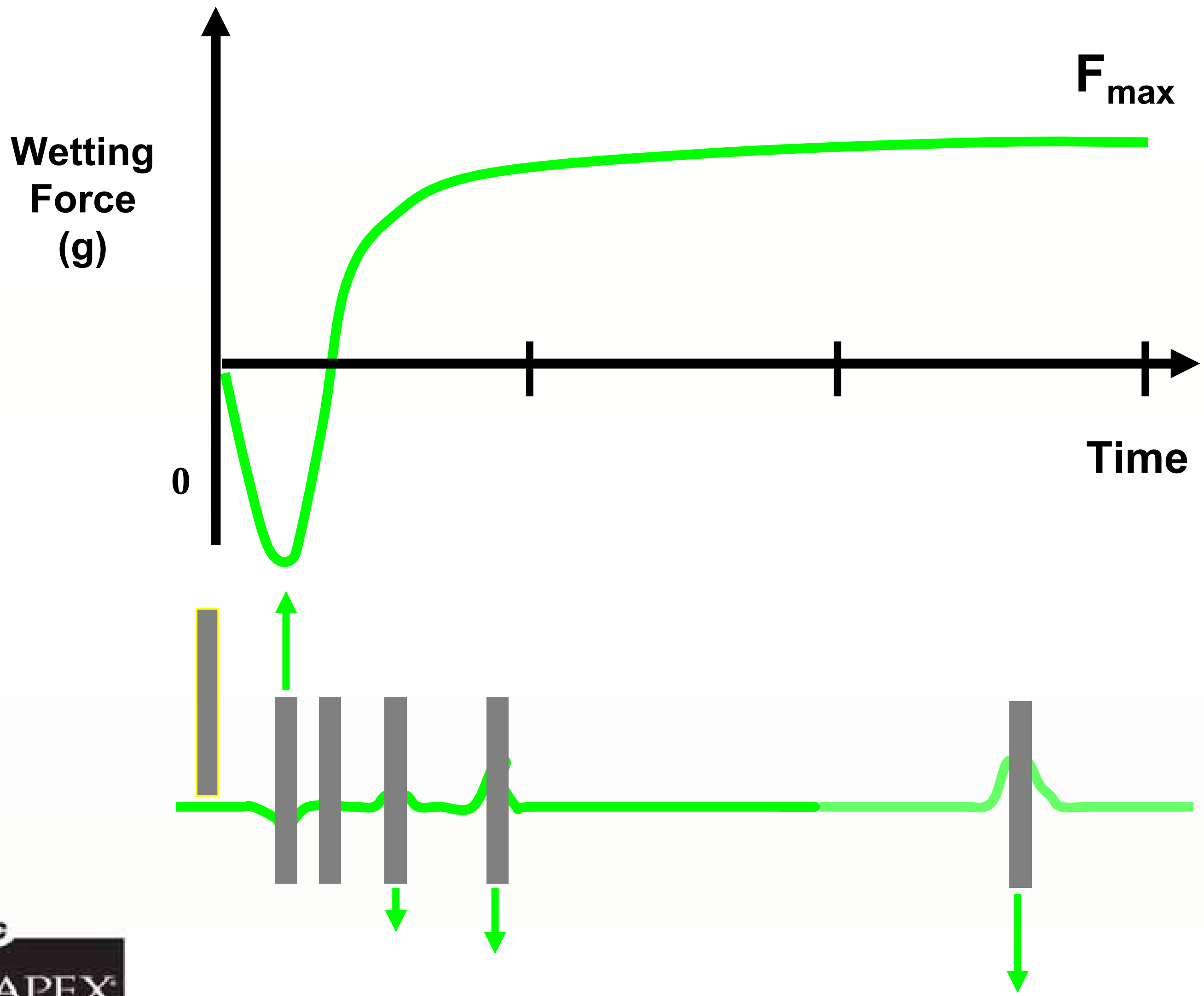
- The initial focus of lead-free alloy development
- Was there anything special about the 183°C melting point of SnPb?
- The important temperature is process temperature
- A higher melting point alloy might need a lower superheat ★

Alloy System	Melting Point ° C	Typical Process Temperatures (° C)		
		Wire	Wave	Reflow
		Tip Temperature	Solder Temperature	Peak Temperature
Sn-Cu	227	330-380	255-270	240-255
Sn-Ag-Cu	217	330-380	255-270	230-255
Sn-Pb	183	330-380	245-260	205-220

★ *Excess of process temperature over melting point*

Properties that Affect Performance in Soldering Processes

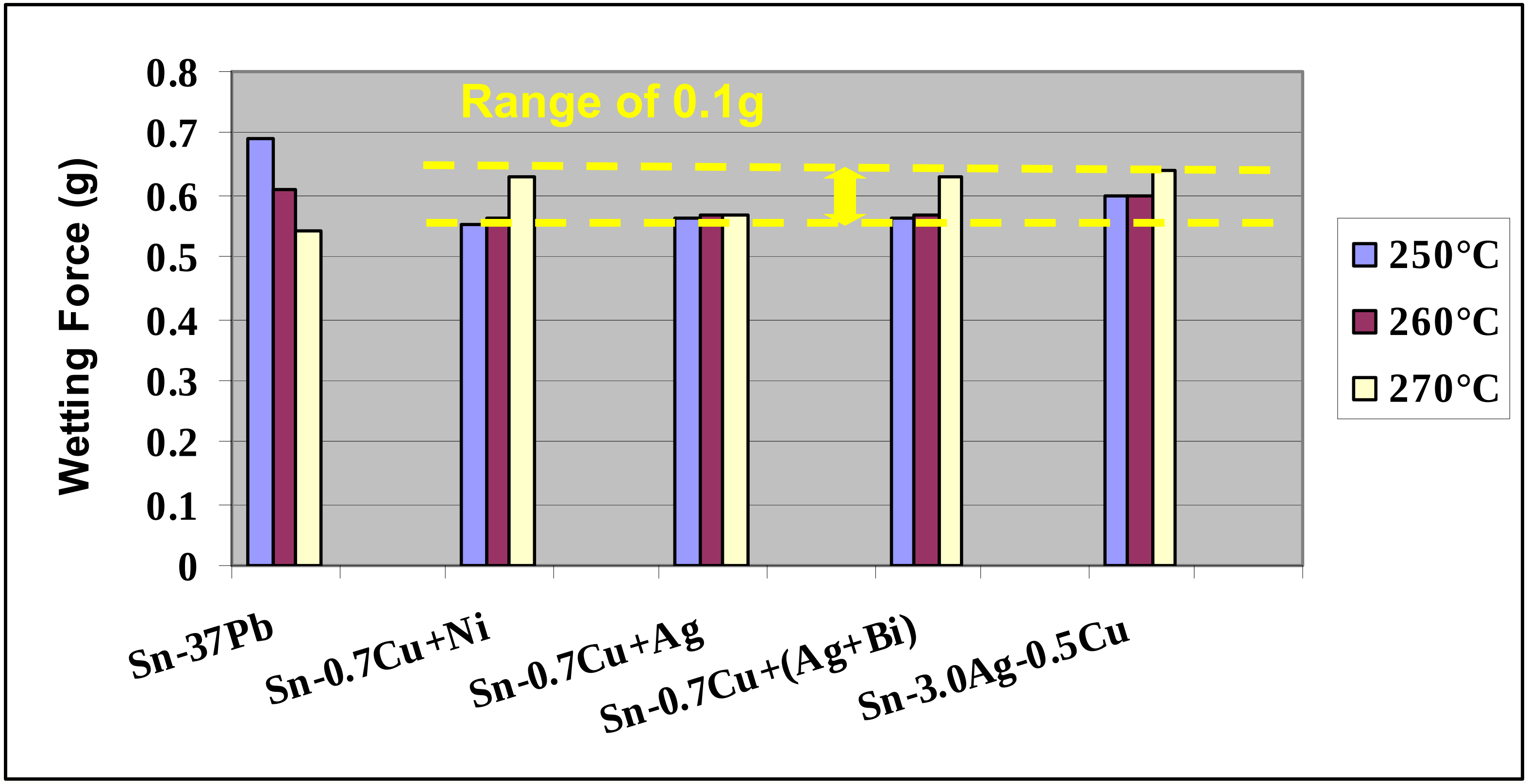
Wetting Properties - The Wetting Balance Test



Properties that Affect Performance in Soldering Processes

Wetting Properties - The Wetting Balance Test

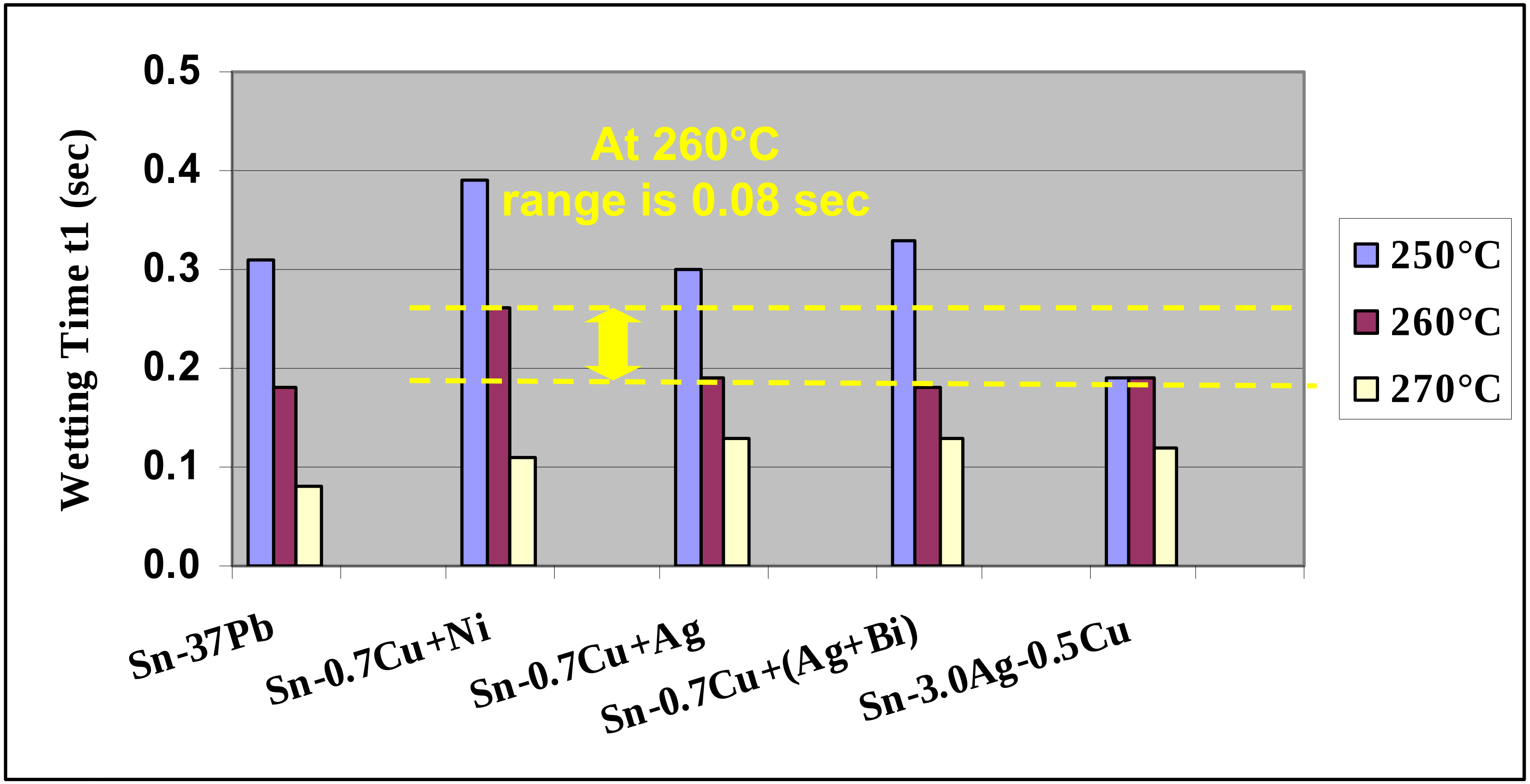
- **<u>Wetting force</u> similar for a range of alloys**
- **<u>Wetting force</u> is a measure of the integrity of the solder/substrate bond**



Properties that Affect Performance in Soldering Processes

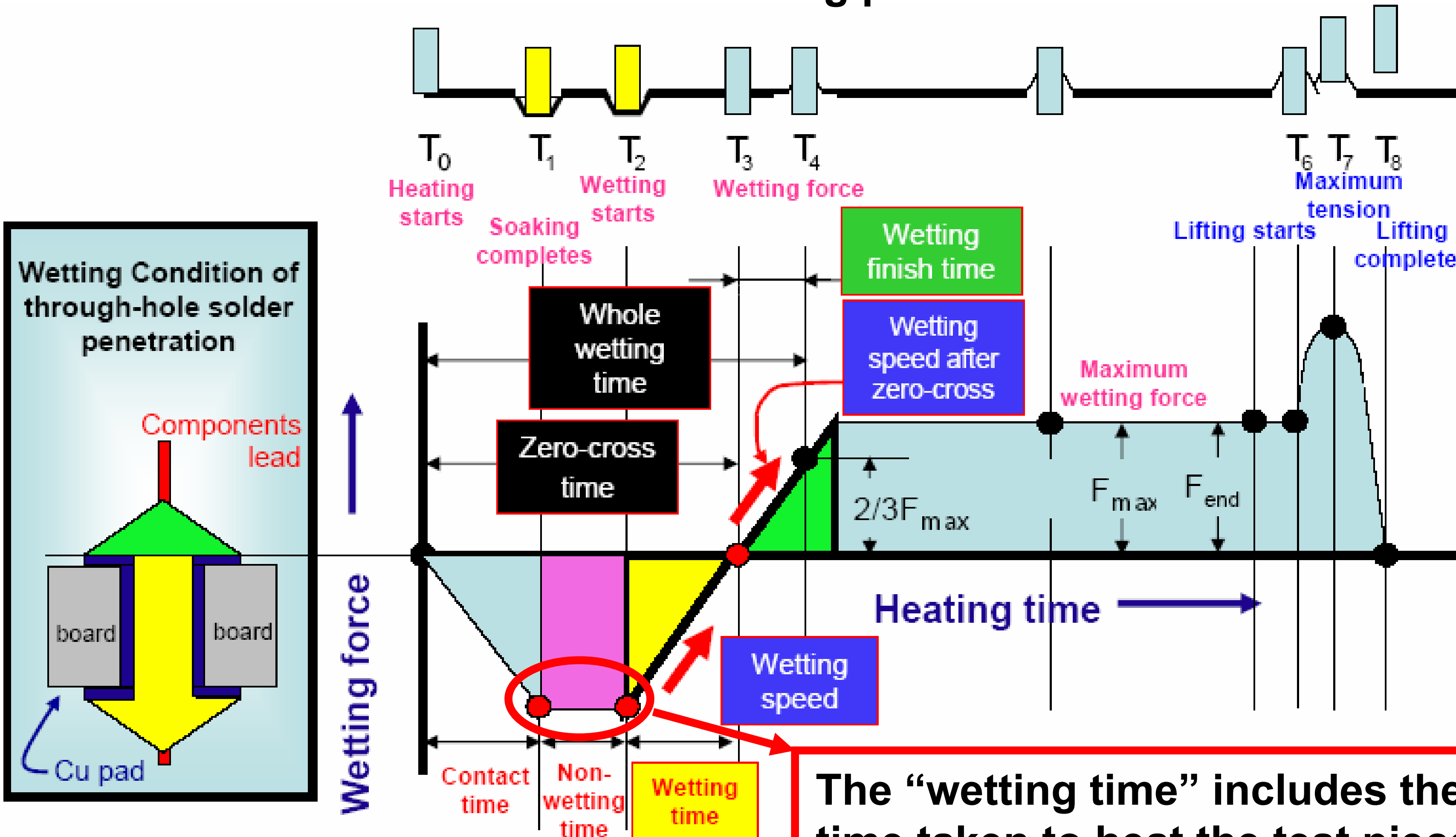
Wetting Properties - The Wetting Balance Test

- Wetting times at 260°C in range of 0.08 seconds
- Wetting time differences decrease as temperature increases



Properties that Affect Performance in Soldering Processes

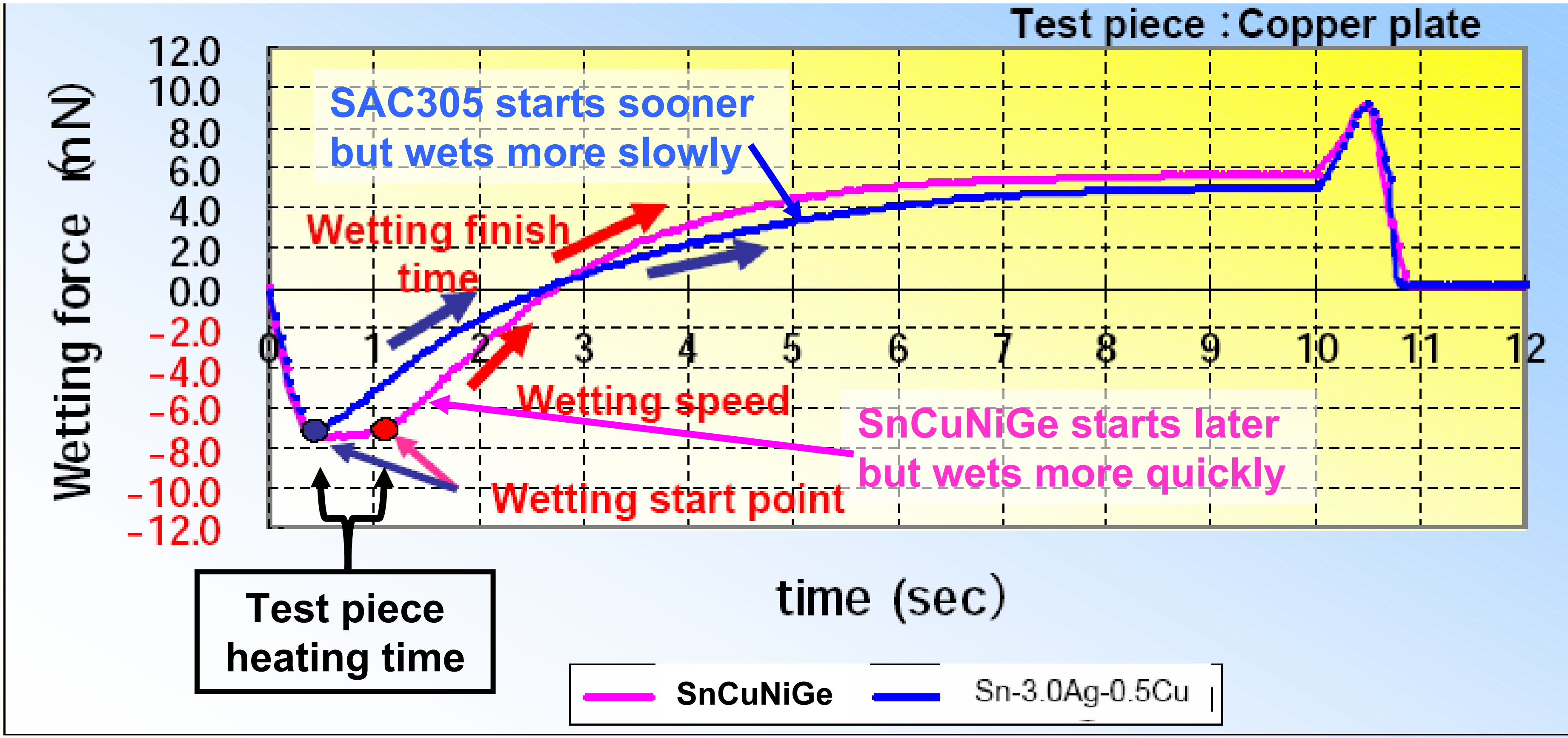
The wetting balance test is not a perfect simulation of soldering processes



The "wetting time" includes the time taken to heat the test piece

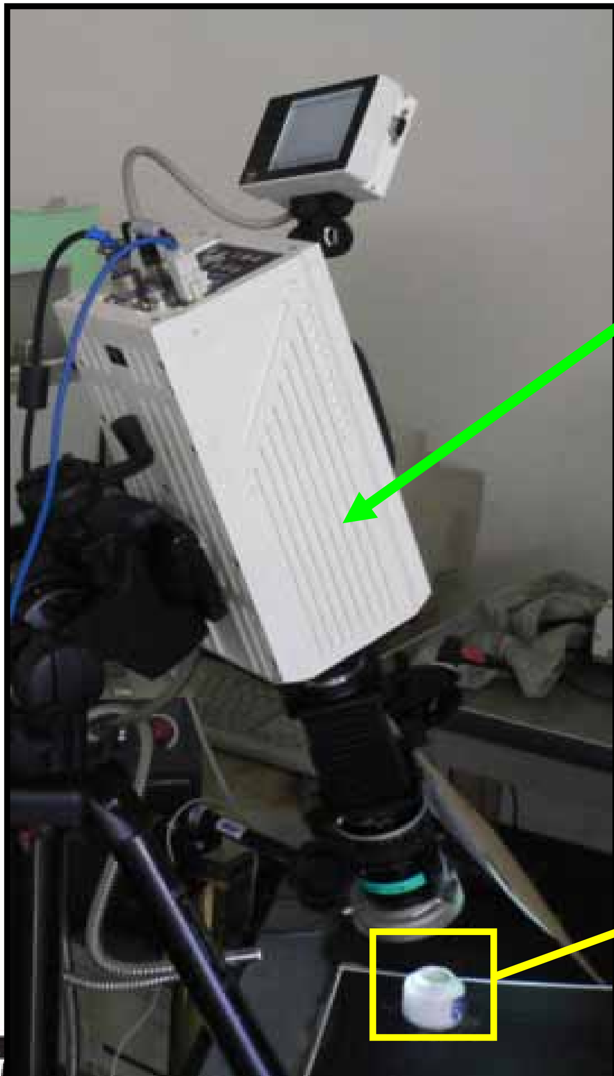
Properties that Affect Performance in Soldering Processes

Unless allowance is made for heating time the wetting time results can be misleading



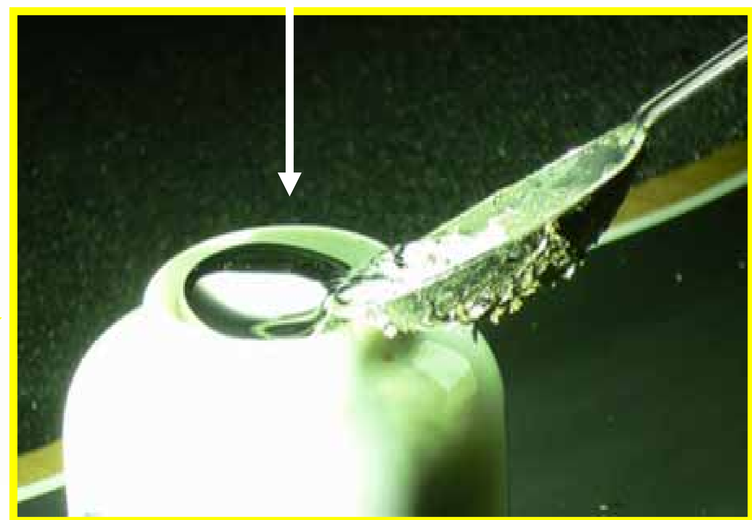
Properties that Affect Performance in Soldering Processes

Solidification mode



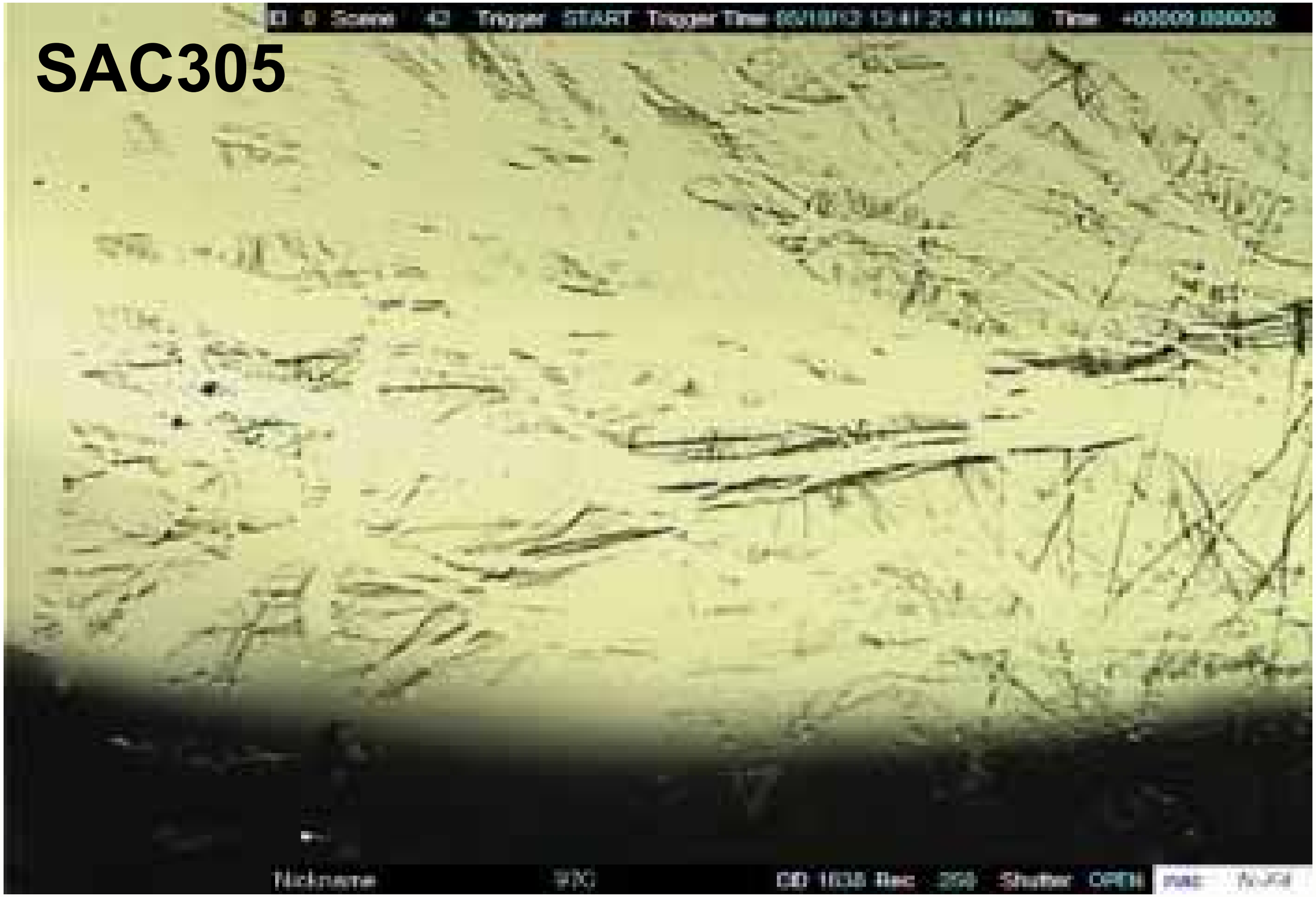
High Speed Video Camera

Crucible of Molten Solder



Properties that Affect Performance in Soldering Processes

Solidification mode



Cooling Rate ~50C/sec

Properties that Affect Performance in Soldering Processes

Solidification mode

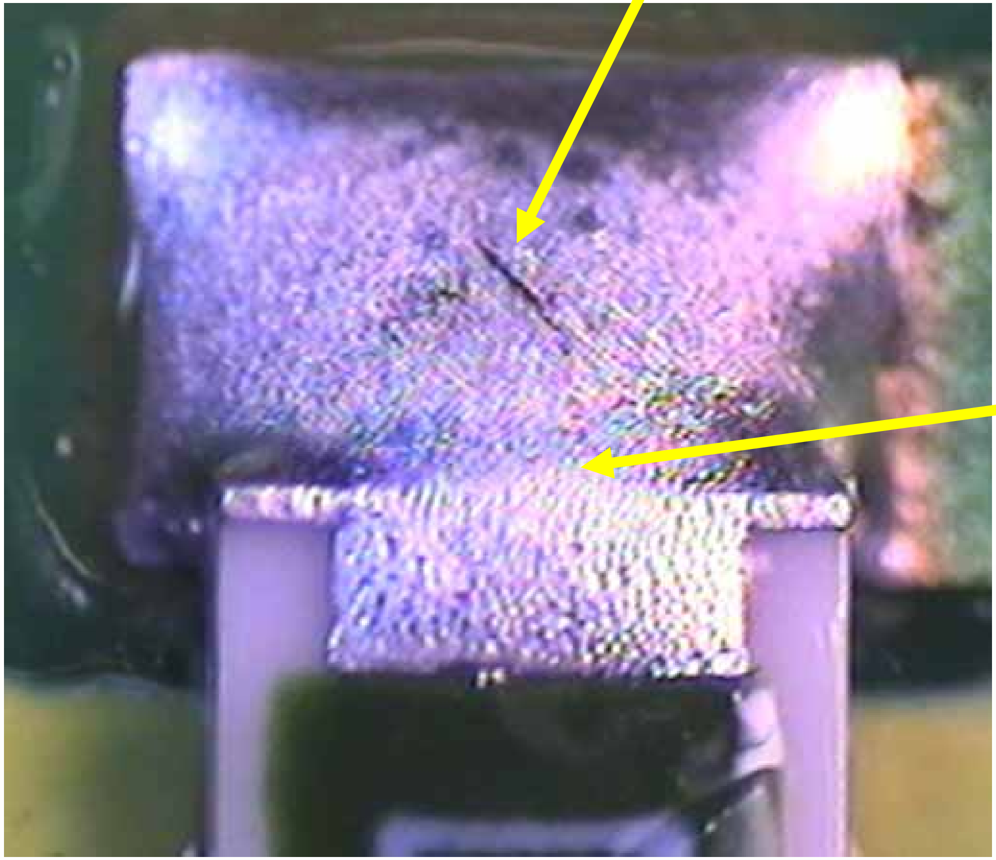
Solidification mode is reflected in the surface appearance of the solder

Fast Cooling **SAC305** **Slow Cooling**

Properties that Affect Performance in Soldering Processes

Solidification mode

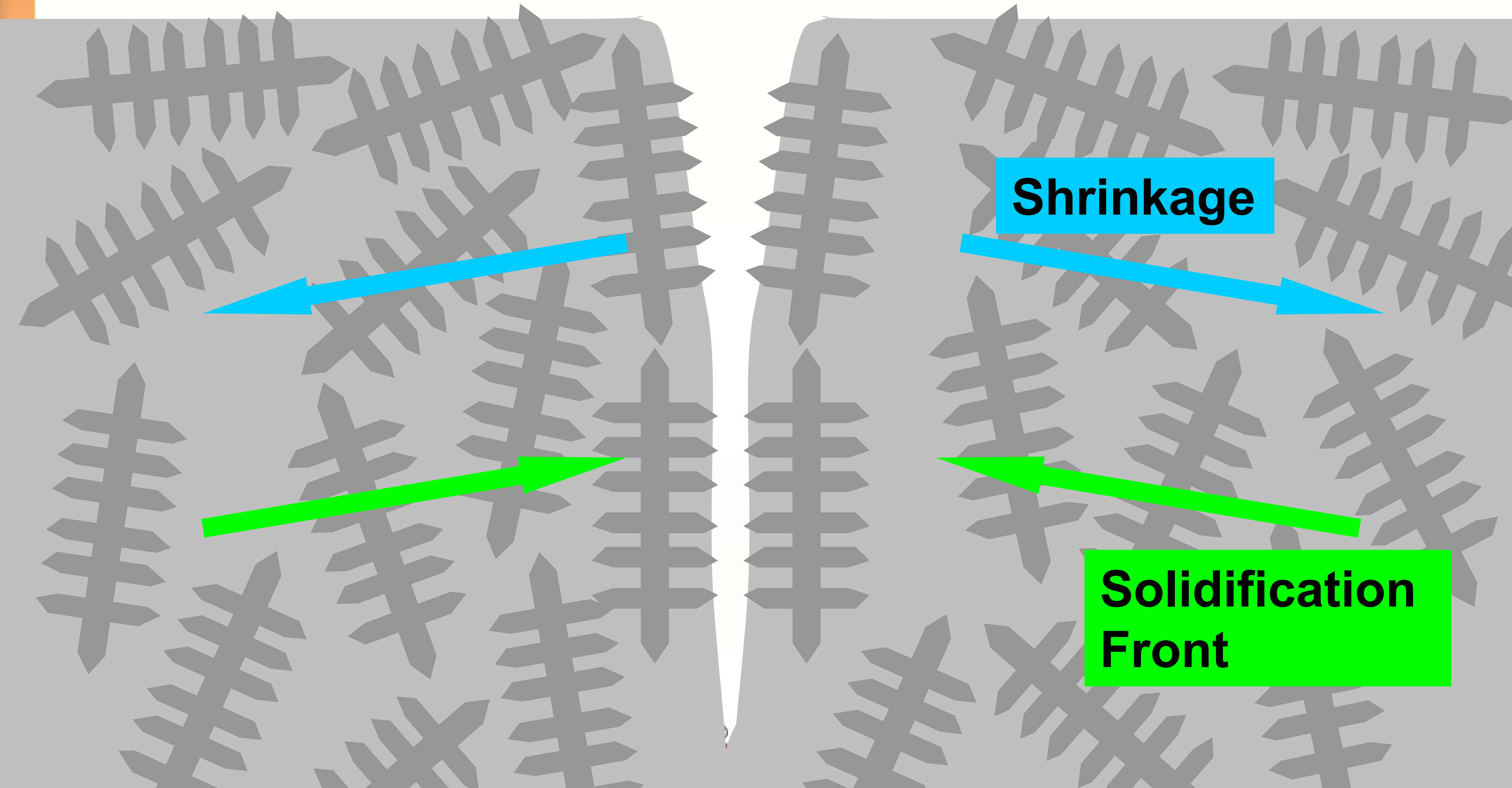
Shrinkage on solidification sometimes results in cavities



Dull grainy finish

Solidification mode

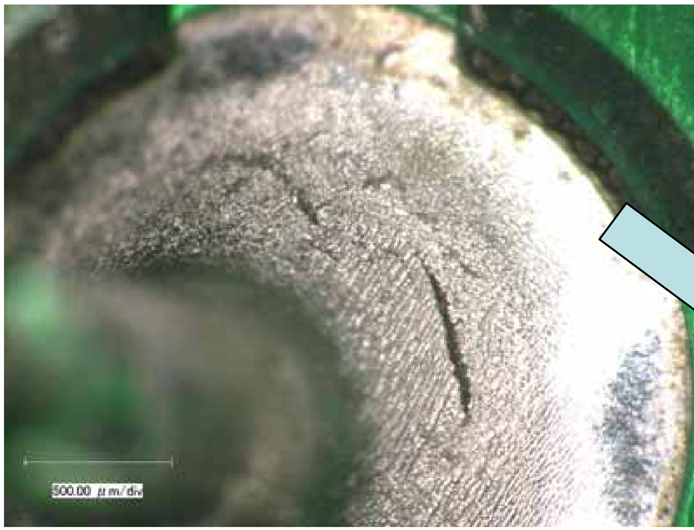
Shrinkage cavities are the result of a two- stage (non-eutectic) solidification mode



Properties that Affect Performance in Soldering Processes

Solidification mode

Shrinkage cavities could be a reliability issue?



1000 cycles
-40/+125°C
30 minute dwells

Solidification mode

Shrinkage cavities could be a reliability issue?

Shrinkage Cavity

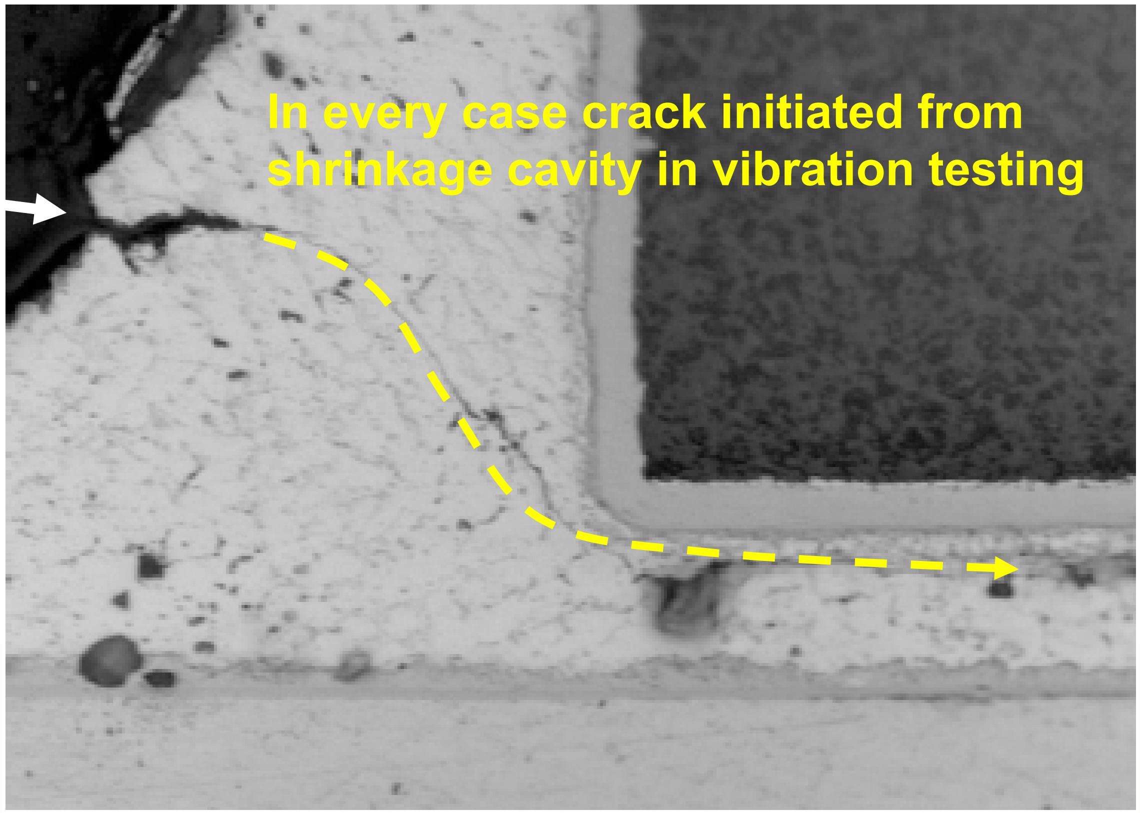


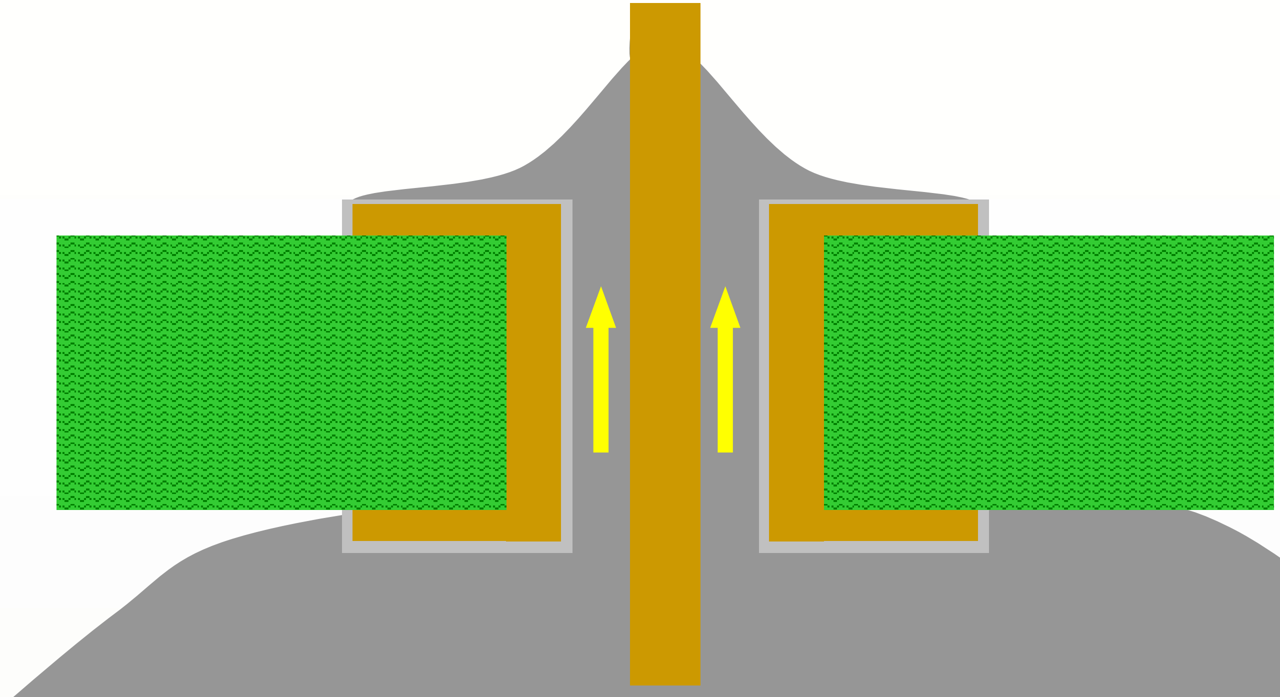
Figure 11: SnAgCu, failed solder joint, 200X

Dr Nathan Blattau, DfR Solutions, SMTAI October 2005

Properties that Affect Performance in Soldering Processes

"Fluidity"

- Not the reciprocal of viscosity
- A term used by the foundry industry as a measure of the ease with which an alloy can flow into the intricate features of a mould.

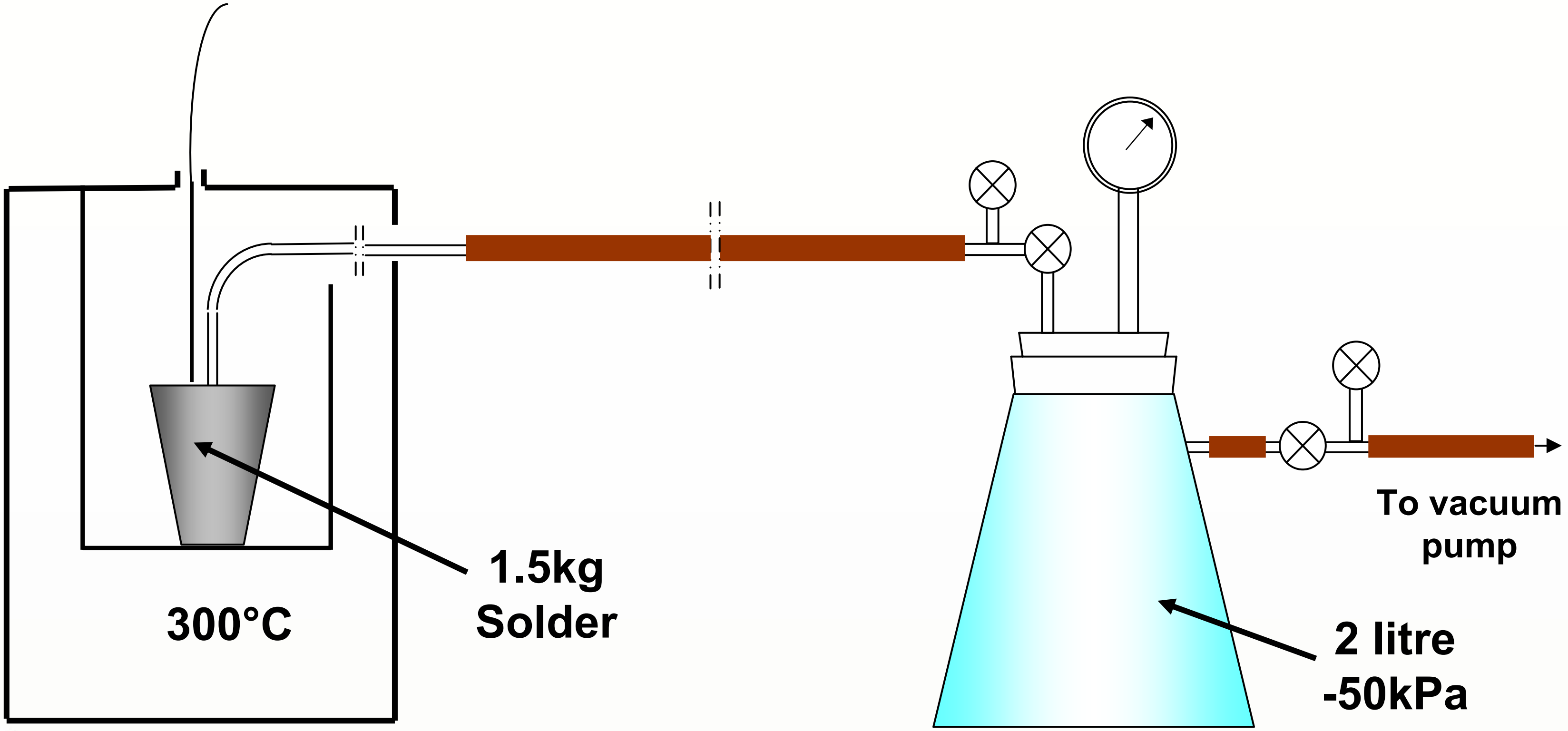


Soldering is a casting operation to the extent that it involves the manipulation and placement of molten metal.

Properties that Affect Performance in Soldering Processes

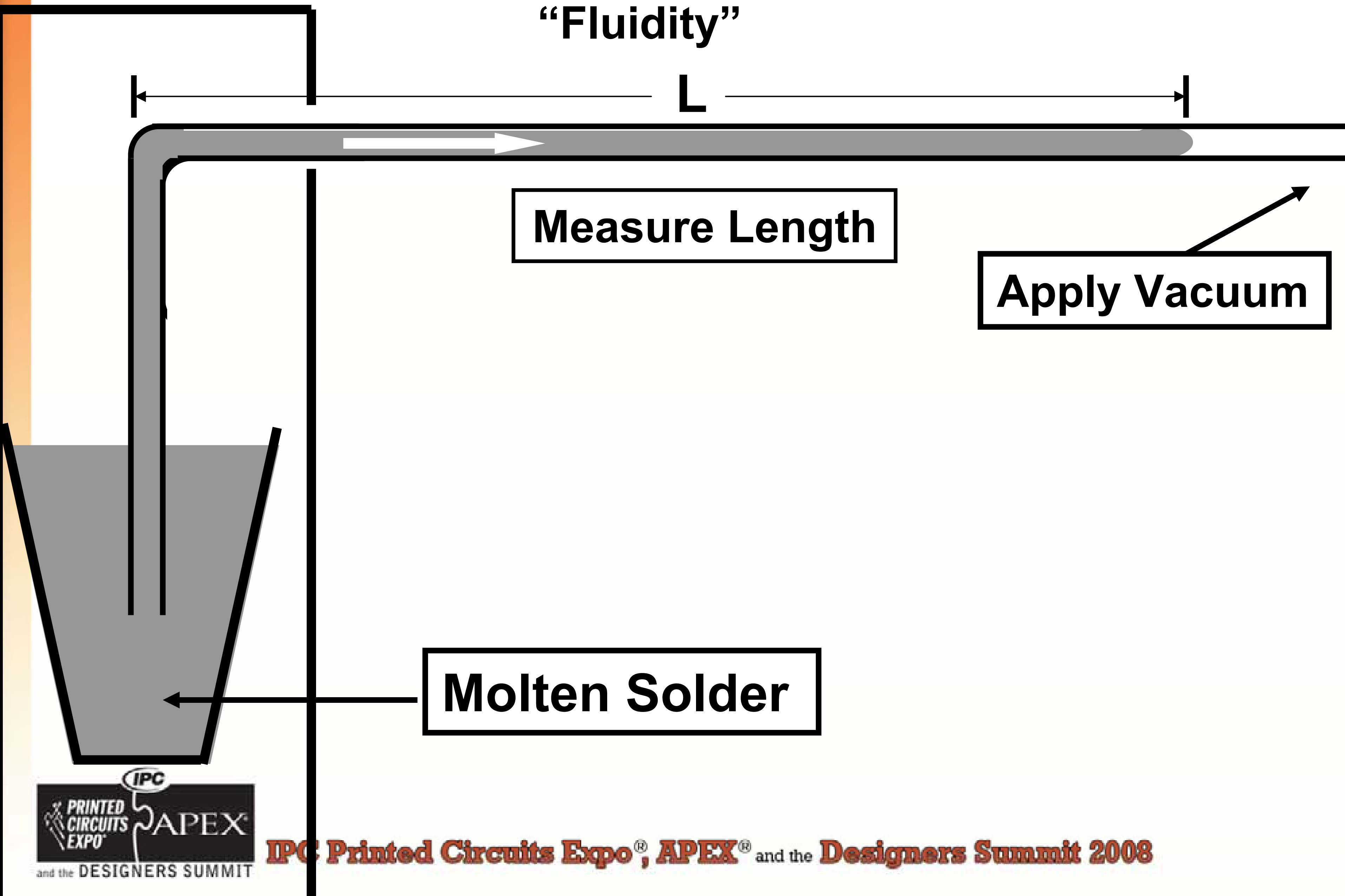
"Fluidity"

Ragone fluidity test



Properties that Affect Performance in Soldering Processes

"Fluidity"

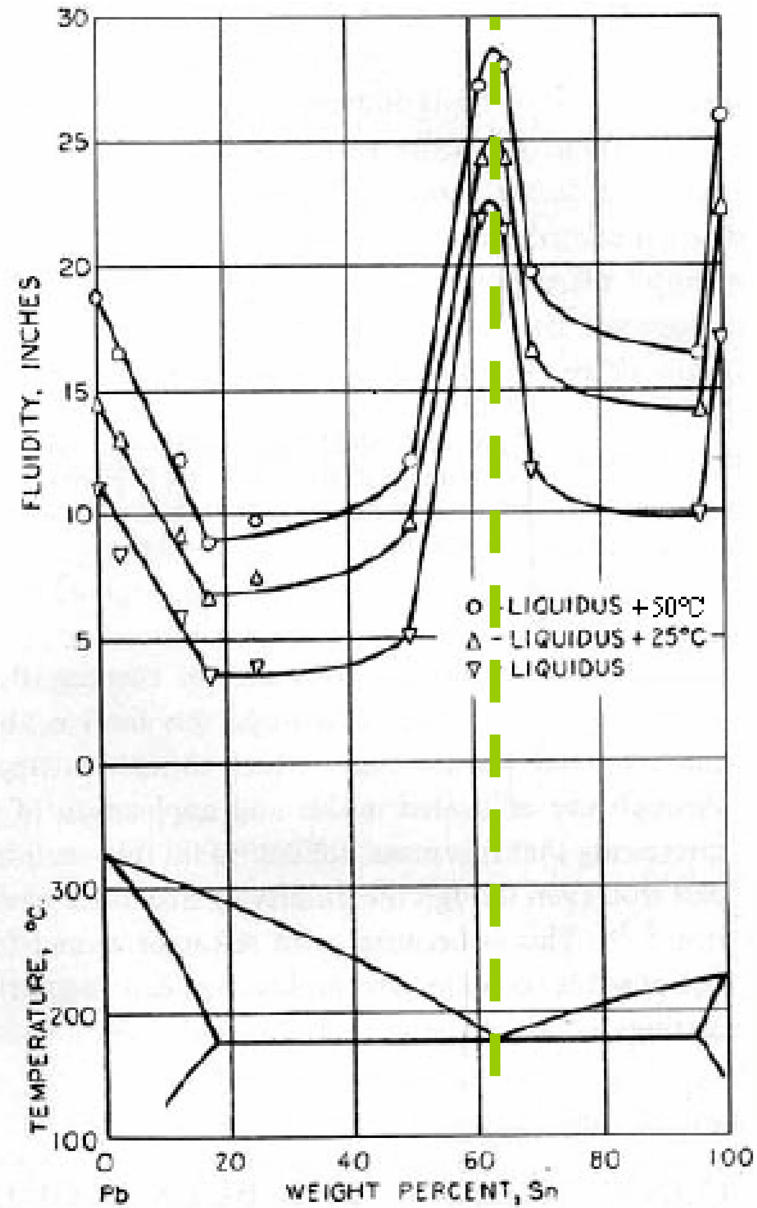


Properties that Affect Performance in Soldering Processes

"Fluidity"

Is Ragone fluidity a relevant property?

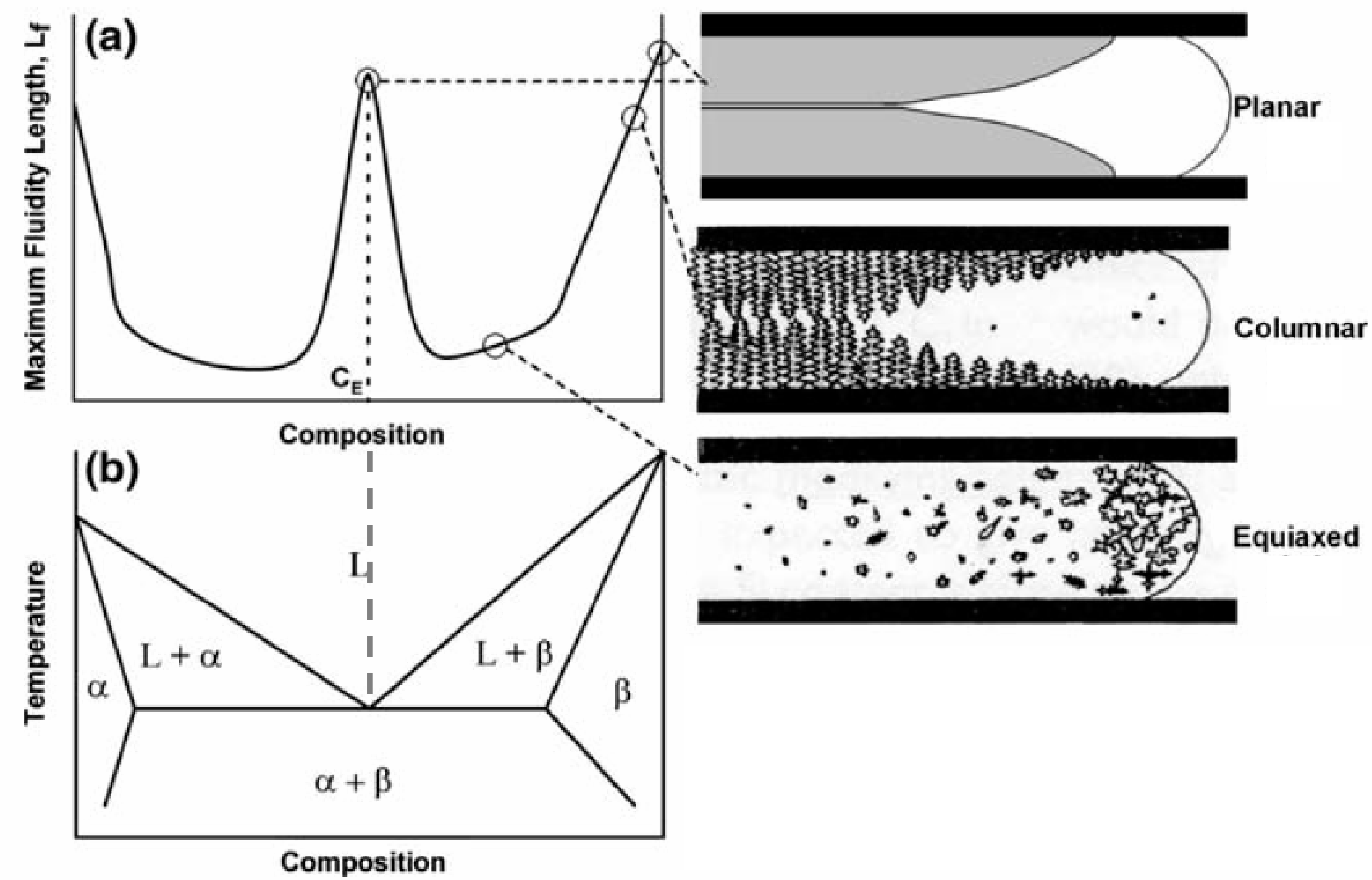
The "63/37" SnPb alloy chosen by the electronics industry as its preferred alloy has the maximum fluidity



Properties that Affect Performance in Soldering Processes

“Fluidity”

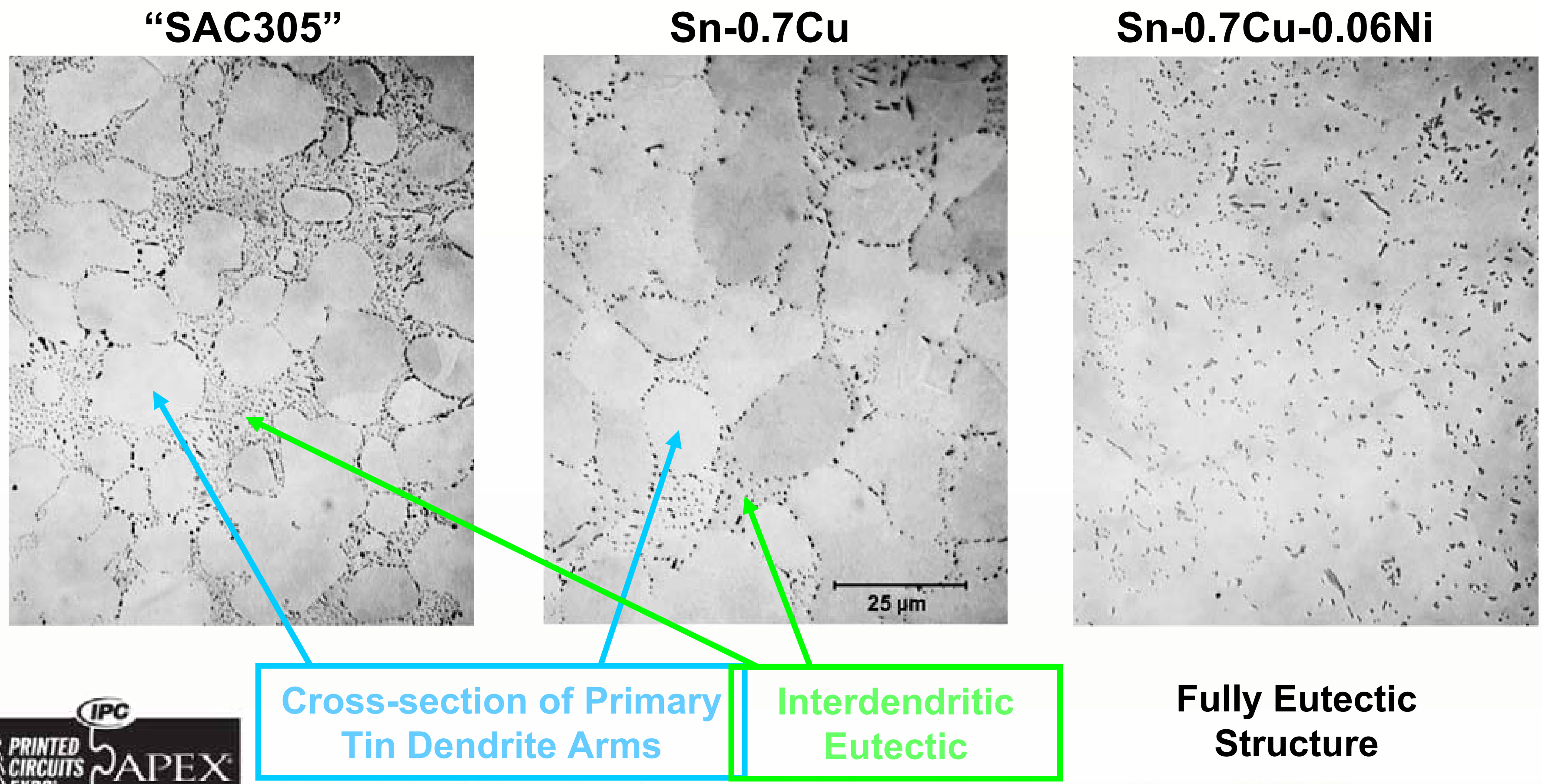
Fluidity provides an indication of solidification mechanism



Properties that Affect Performance in Soldering Processes

"Fluidity"

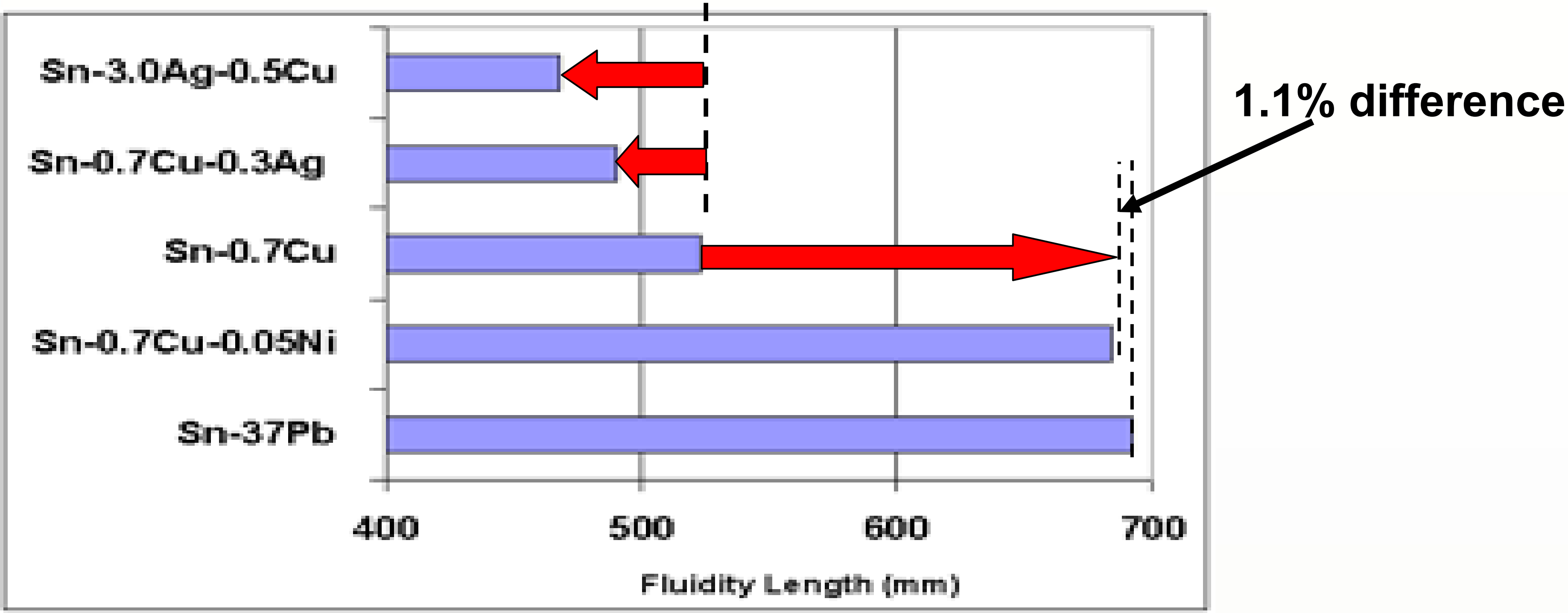
Cross-sections of fluidity test pieces



Properties that Affect Performance in Soldering Processes

"Fluidity"

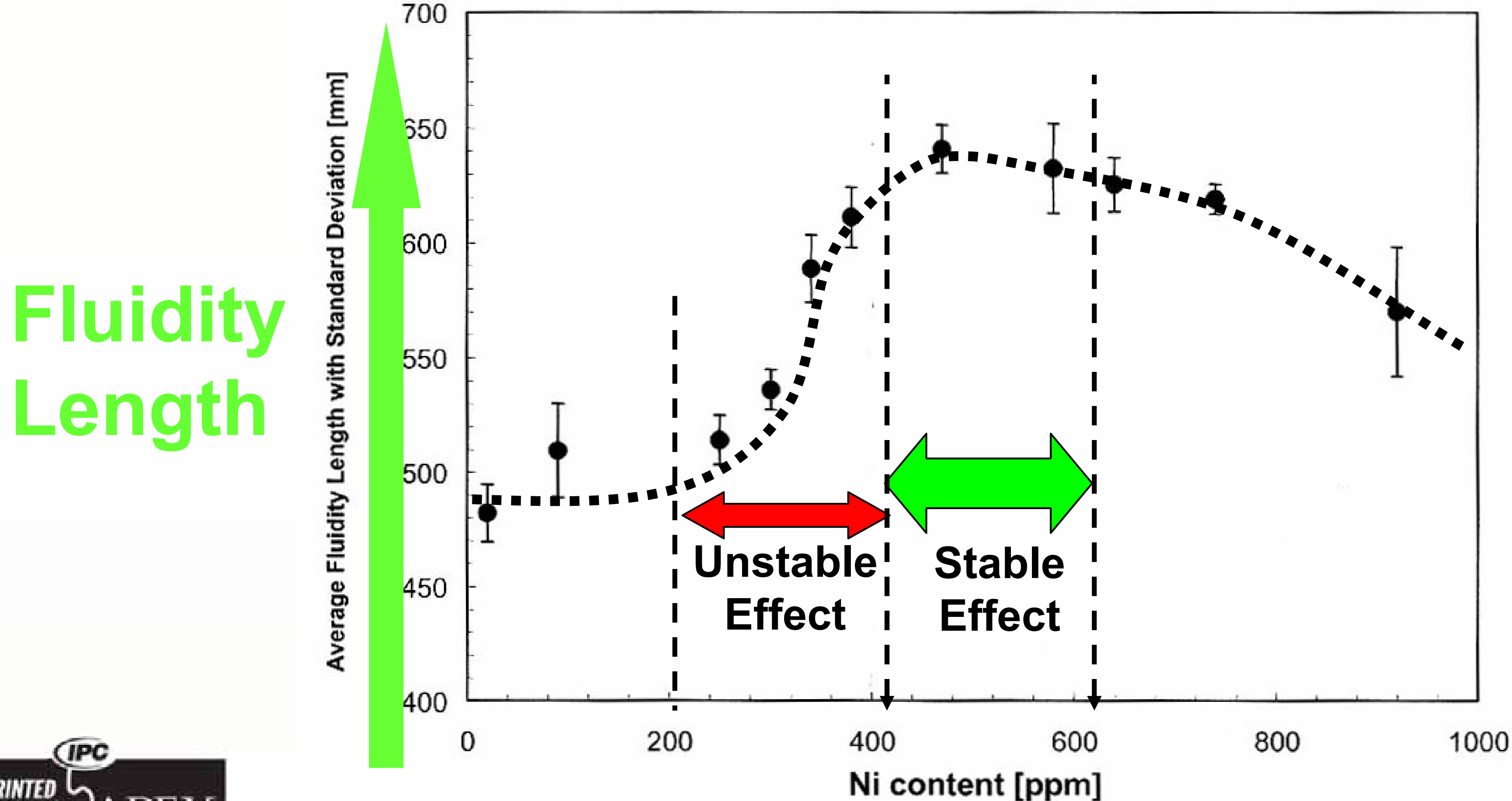
- **Eutectic behavior is reflected in Ragone fluidity**
  - **SnCuNi matches the fluidity of Sn-37Pb at same superheat**



Properties that Affect Performance in Soldering Processes

"Fluidity"

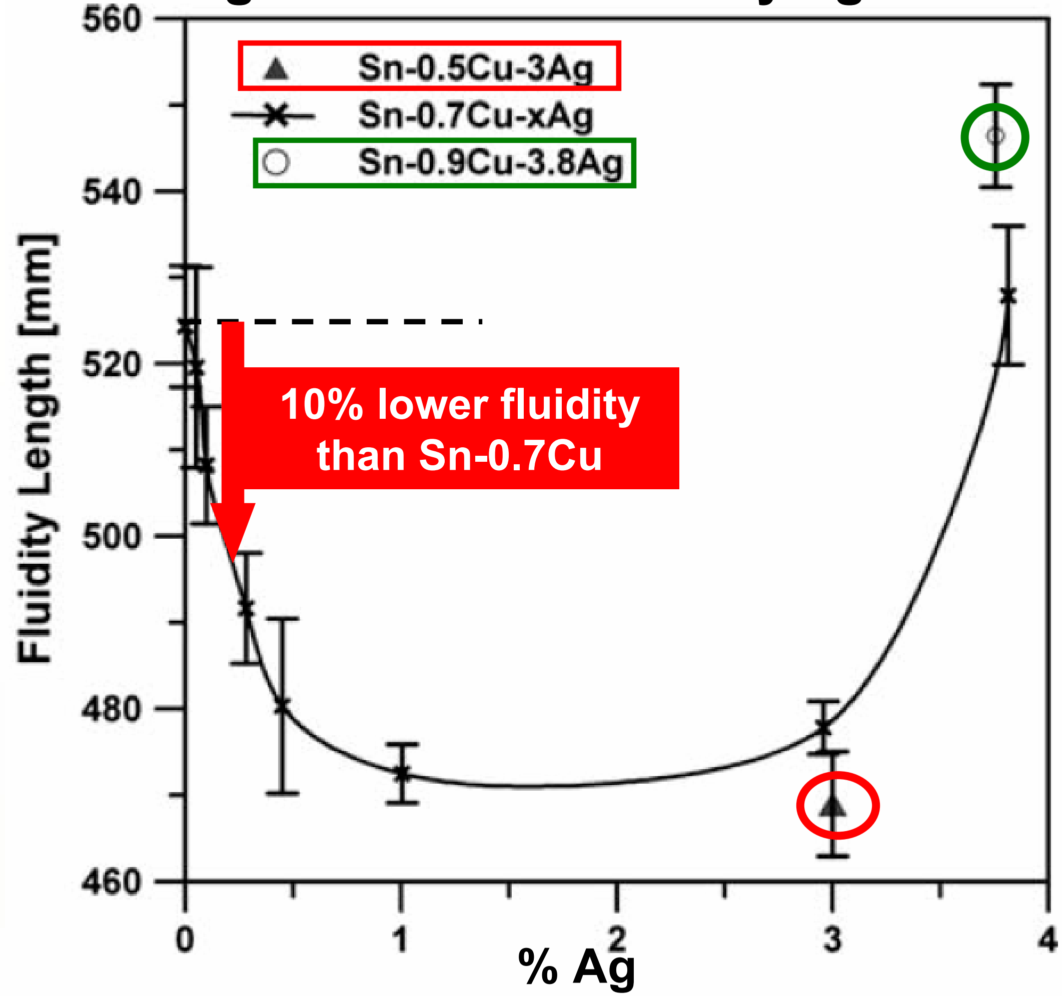
For microalloyed solders it can be important to keep the level of the critical elements in the right range



Properties that Affect Performance in Soldering Processes

"Fluidity"

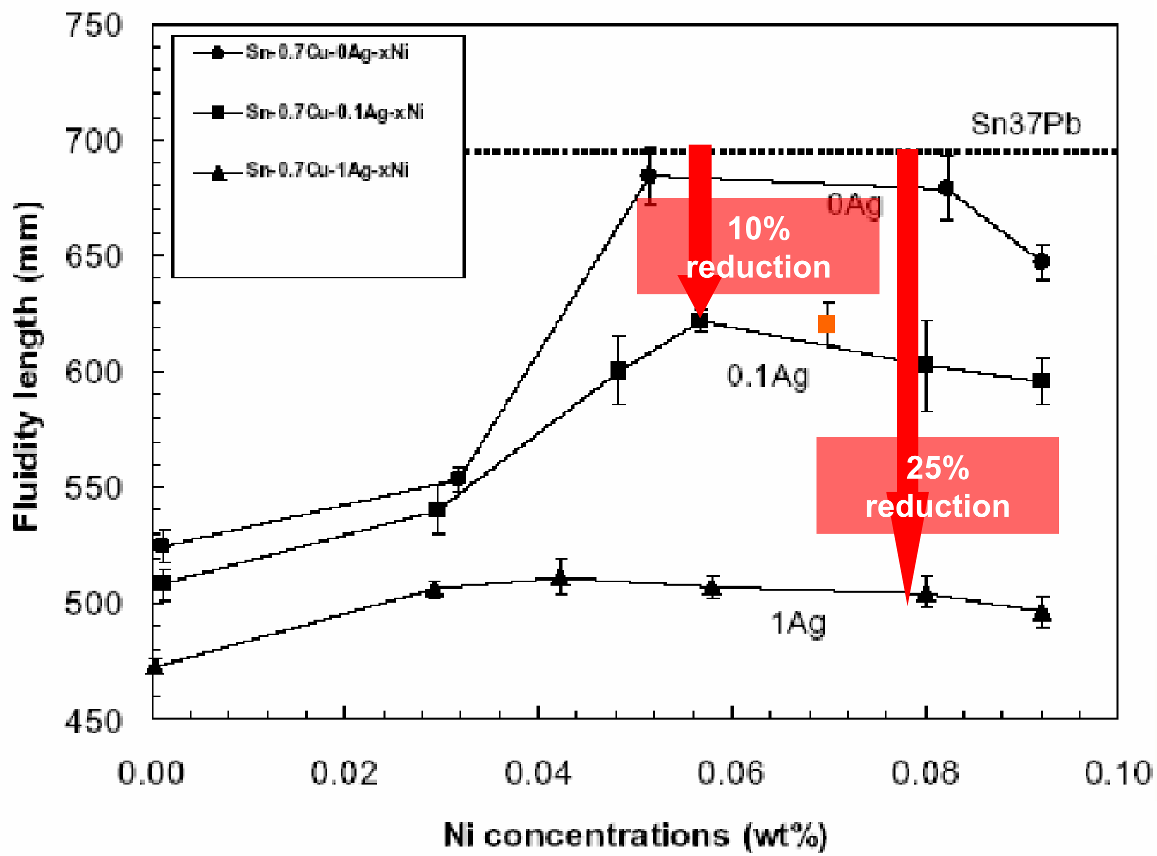
A fluidity measurement provides an additional method for assessing the effect of an alloying addition



Properties that Affect Performance in Soldering Processes

"Fluidity"

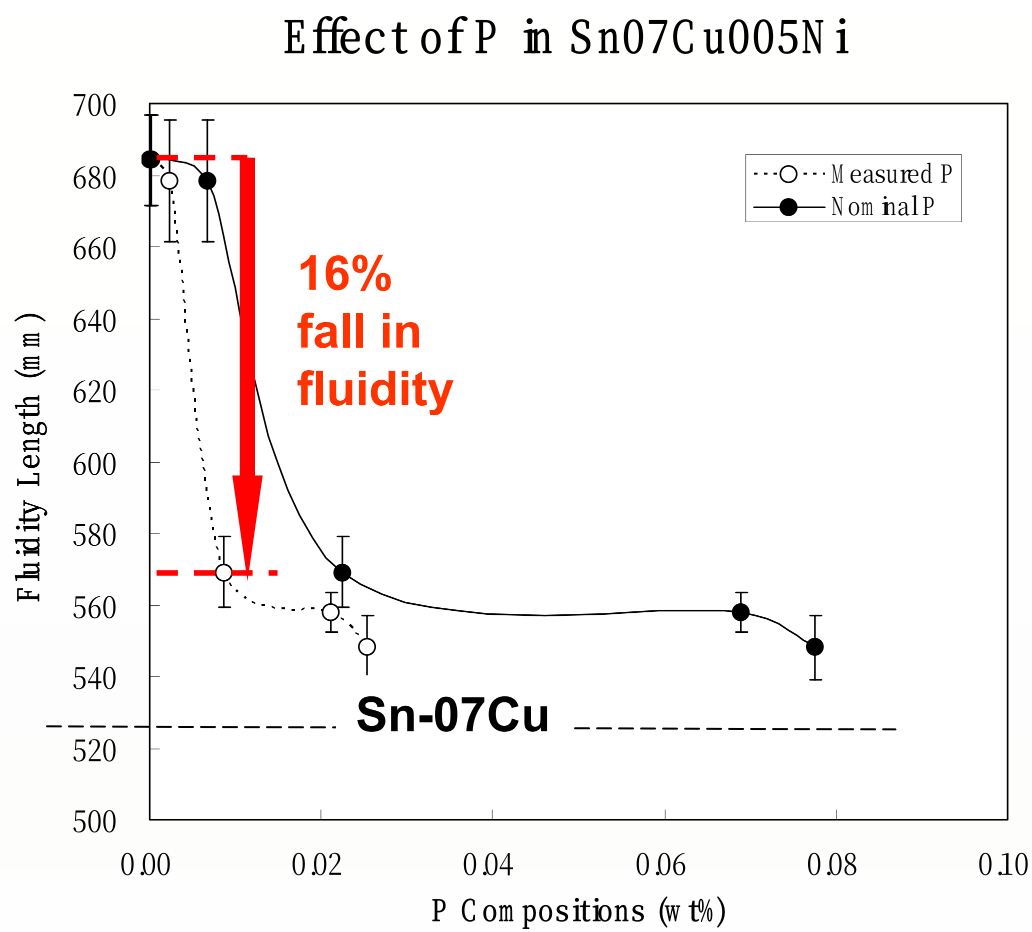
A fluidity measurement provides an additional method for assessing the effect of an alloying addition



Properties that Affect Performance in Soldering Processes

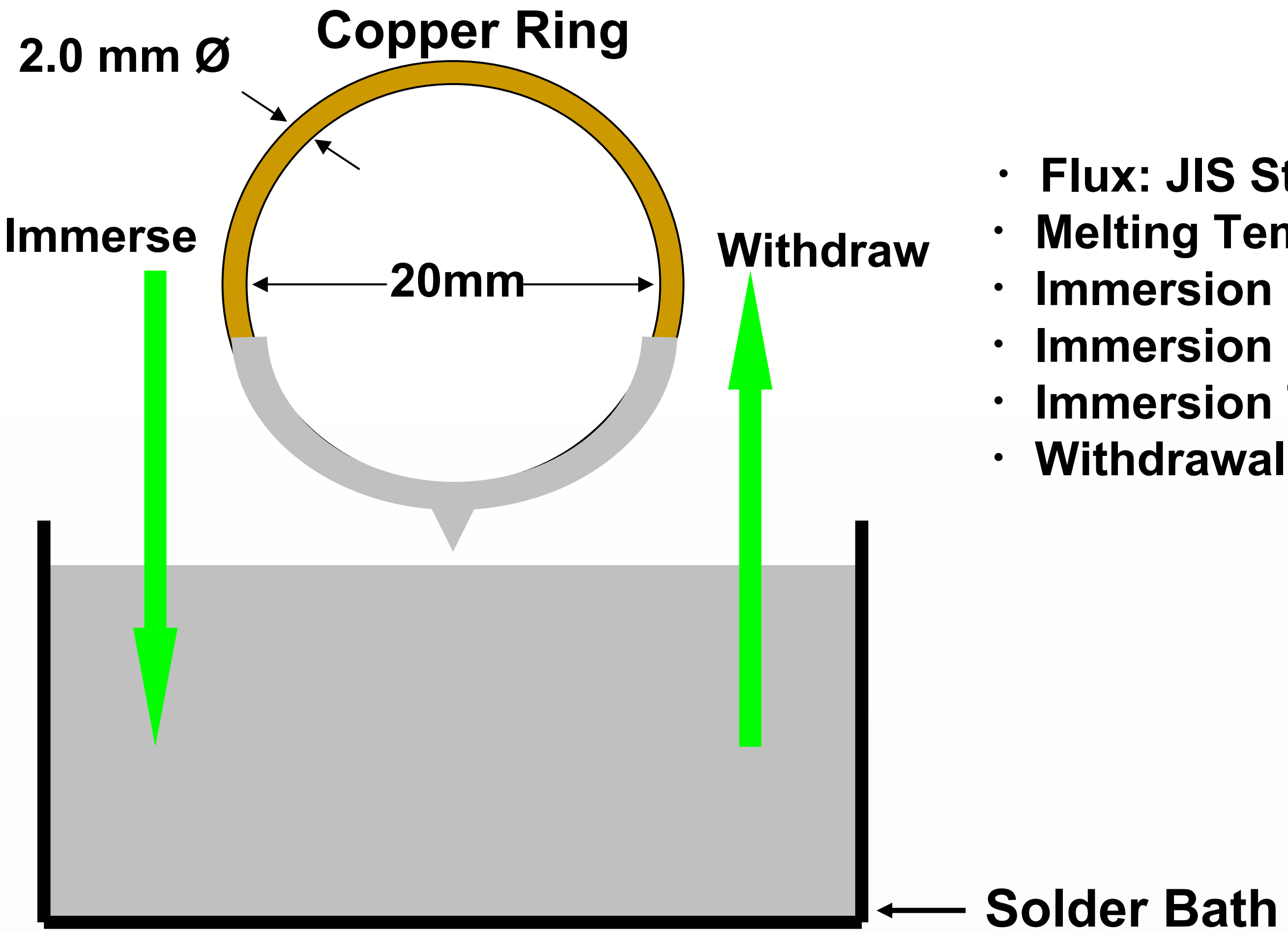
"Fluidity"

Phosphorus additions largely destroy the beneficial effect of nickel addition to the Sn-0.7Cu alloy



Properties that Affect Performance in Soldering Processes

"Drainage"



- Flux: JIS Standard Flux A、B
- Melting Temp.: 255 °C
- Immersion Depth: 6mm
- Immersion Speed: 4mm/s
- Immersion Time: 20 s
- Withdrawal Speed: 2mm/s

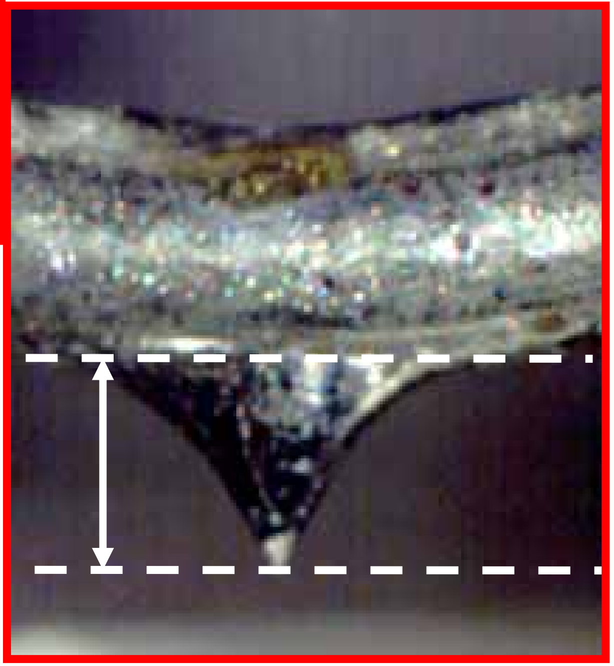
Properties that Affect Performance in Soldering Processes

"Drainage"

Properties that Affect Performance in Soldering Processes

"Drainage"

Icicle
Length



Properties that Affect Performance in Soldering Processes

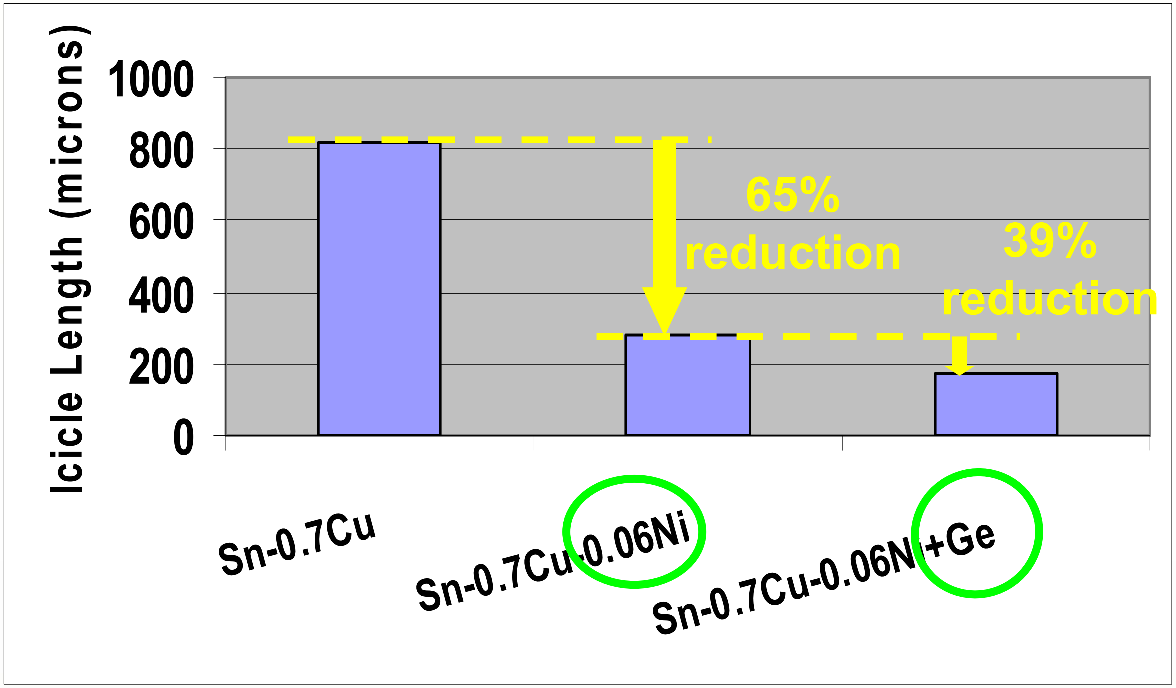
"Drainage"

The ability of solder to drain affects the incidence of shorts in wave soldering but is also relevant to the performance of the solder in other applications

Properties that Affect Performance in Soldering Processes

"Drainage"

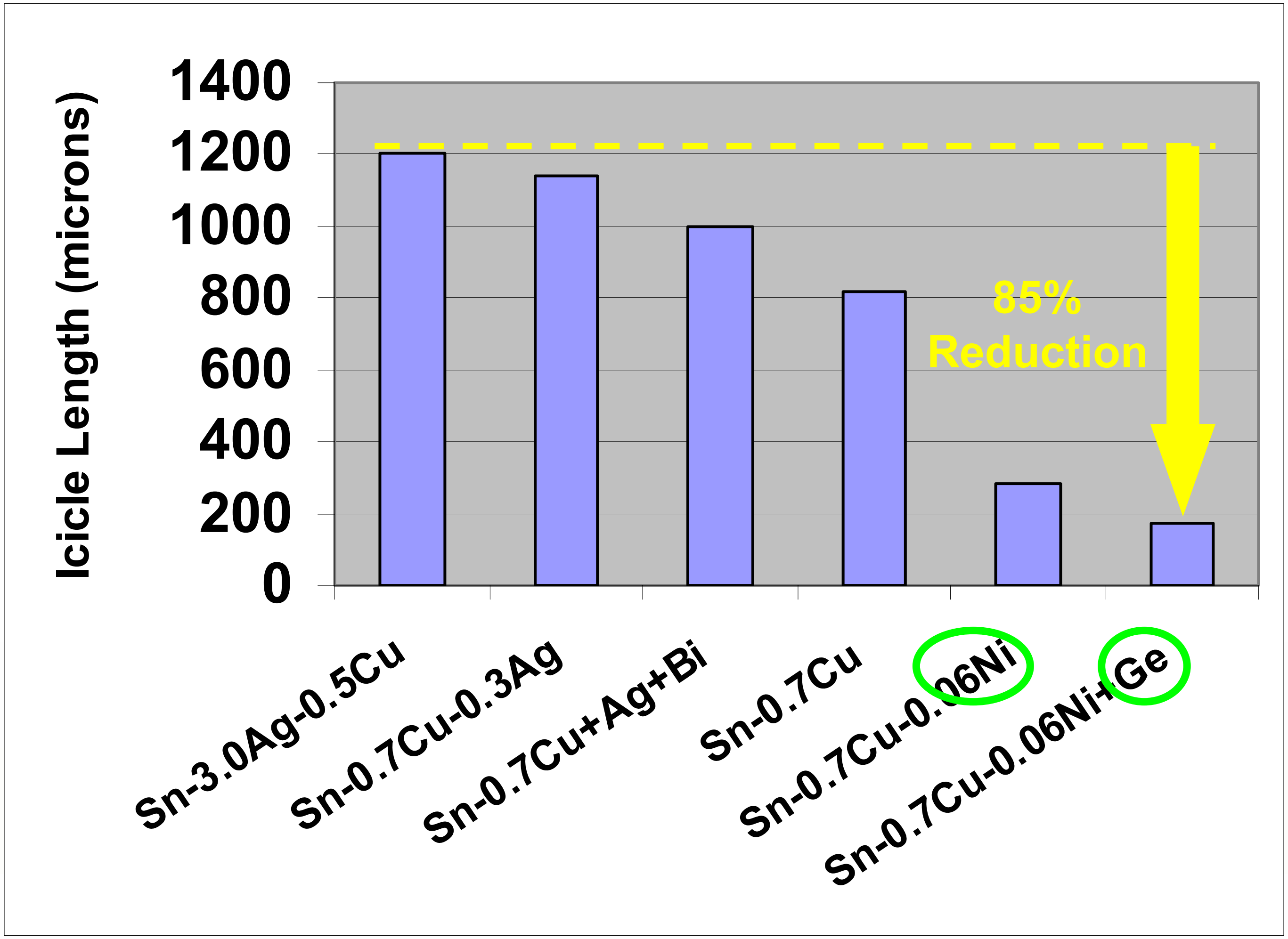
Effect of Ni and Ge additions on icicle length



Properties that Affect Performance in Soldering Processes

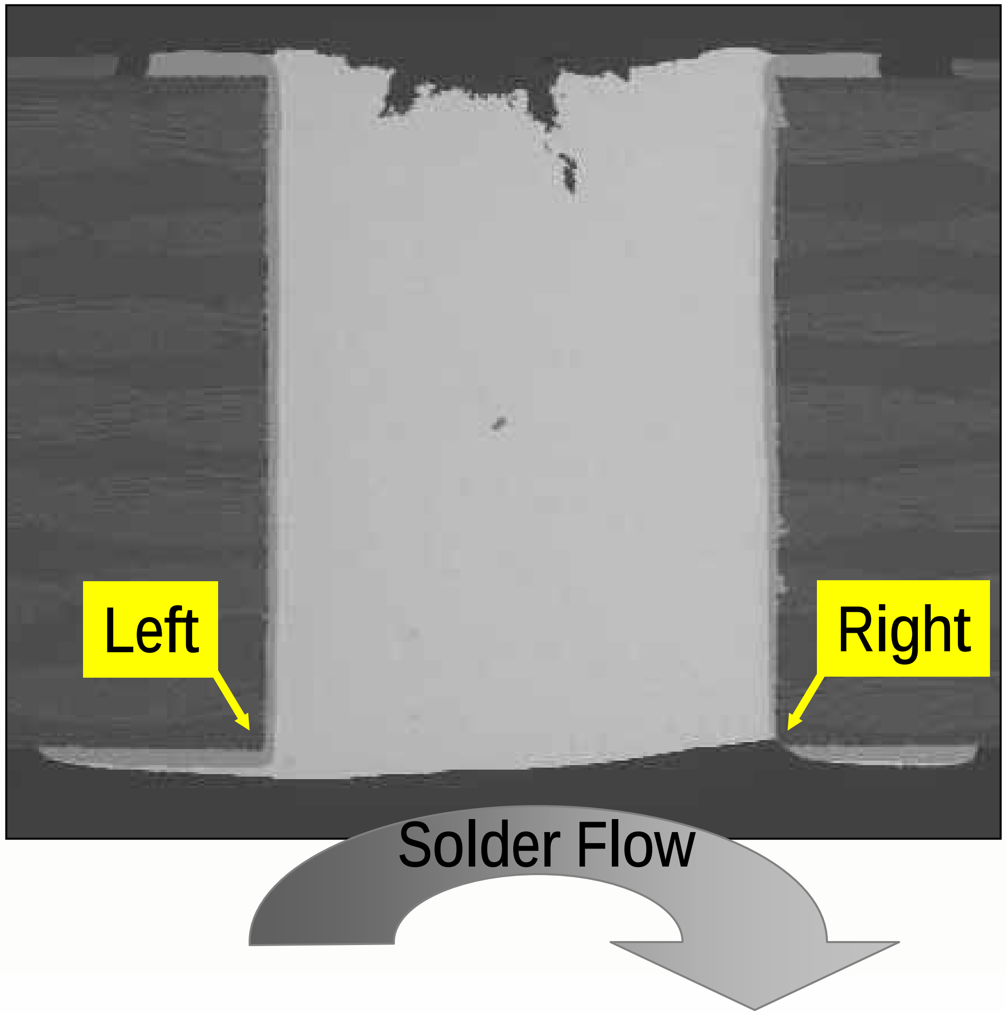
"Drainage"

Effect of Ni and Ge additions on icicle length



Properties that Affect Performance in Soldering Processes

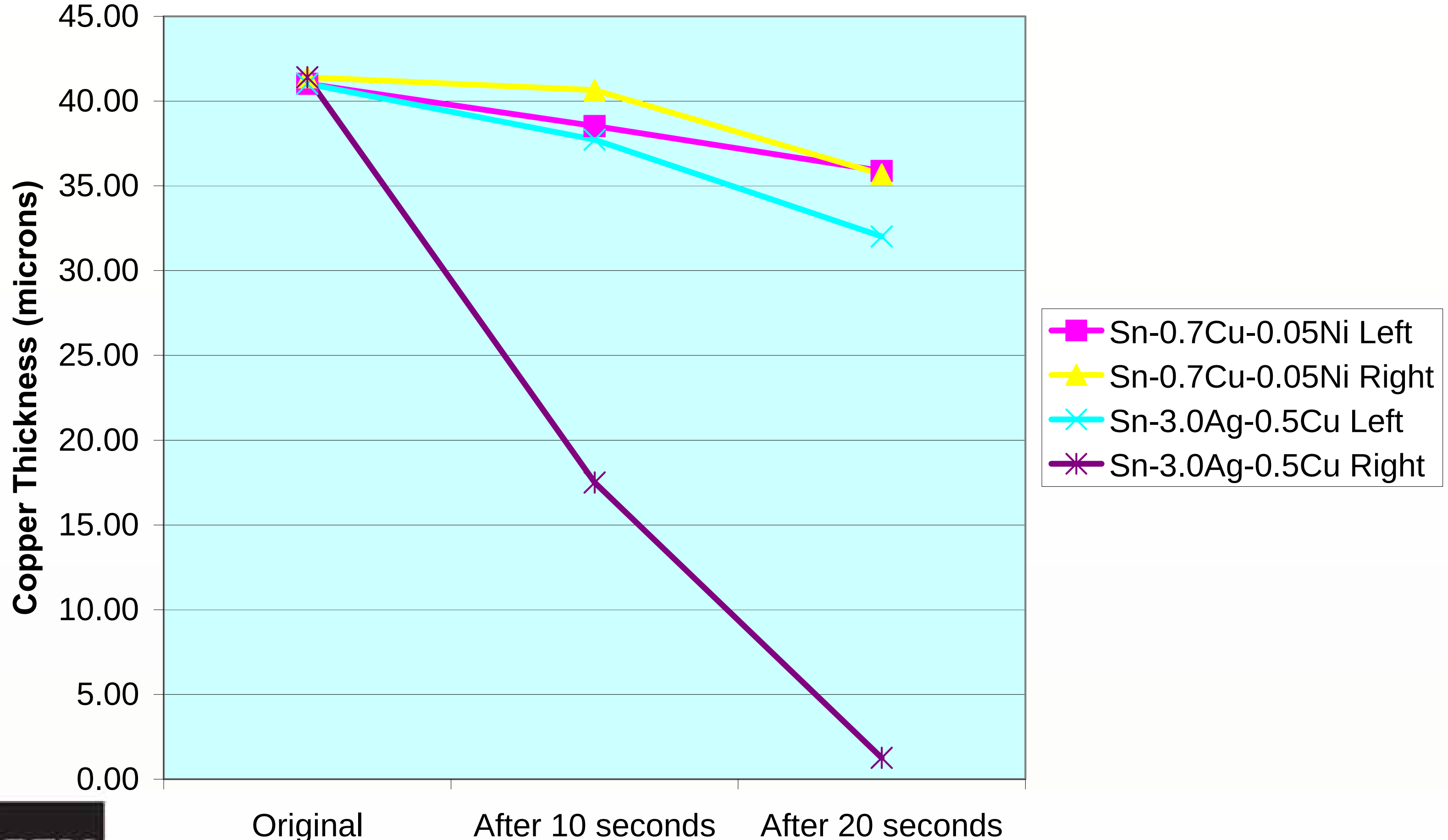
Aggressiveness Towards Copper



Properties that Affect Performance in Soldering Processes

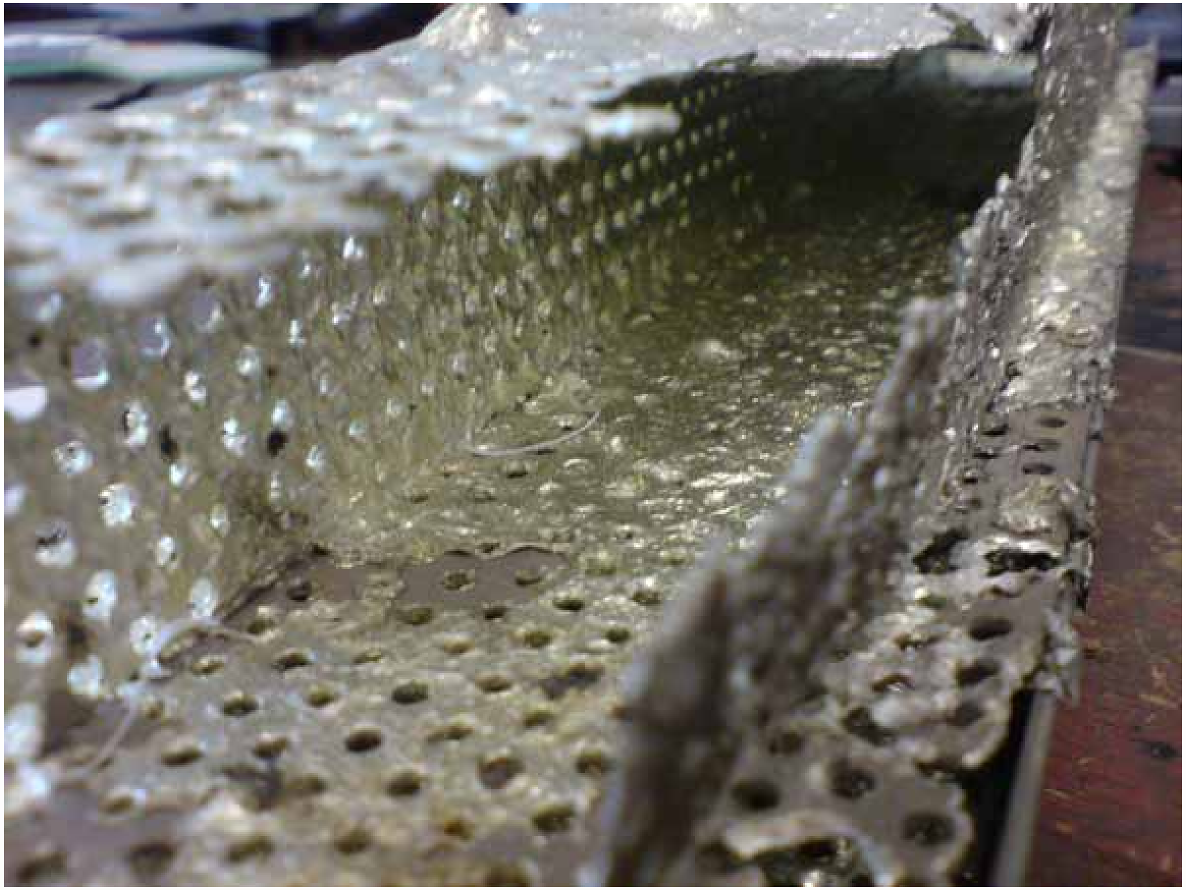
Aggressiveness Towards Copper

Erosion as a Function of Time at 250°C



Properties that Affect Performance in Soldering Processes

Aggressiveness Towards Stainless Steel

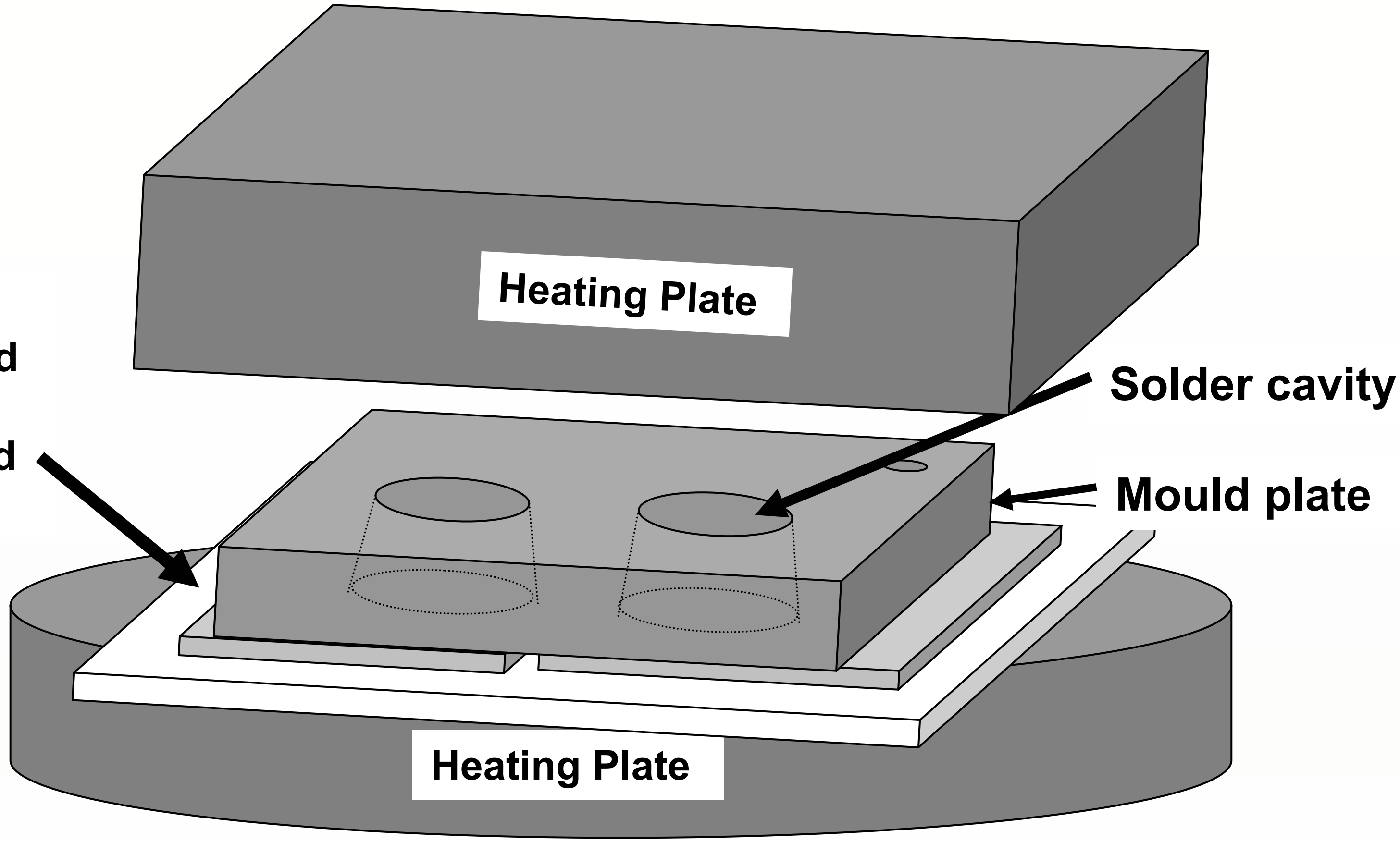


Properties that Affect Performance in Soldering Processes

Aggressiveness Towards Stainless Steel

Experimental Procedure

Stainless Steel Coupons Polished with 1500# emery paper and washed in acetone



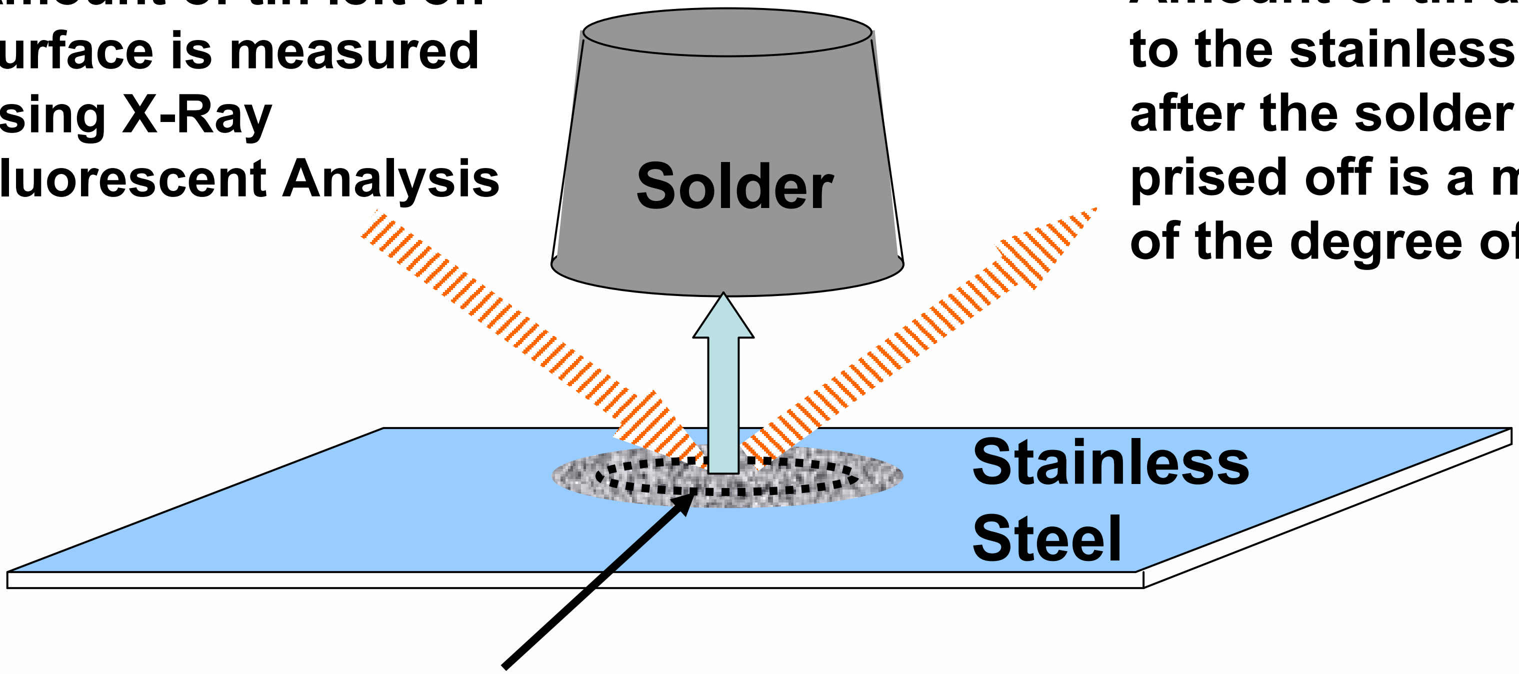
Properties that Affect Performance in Soldering Processes

Aggressiveness Towards Stainless Steel

Experimental Procedure

Amount of tin left on surface is measured using X-Ray Fluorescent Analysis

Amount of tin adhering to the stainless steel after the solder slug is prised off is a measure of the degree of wetting

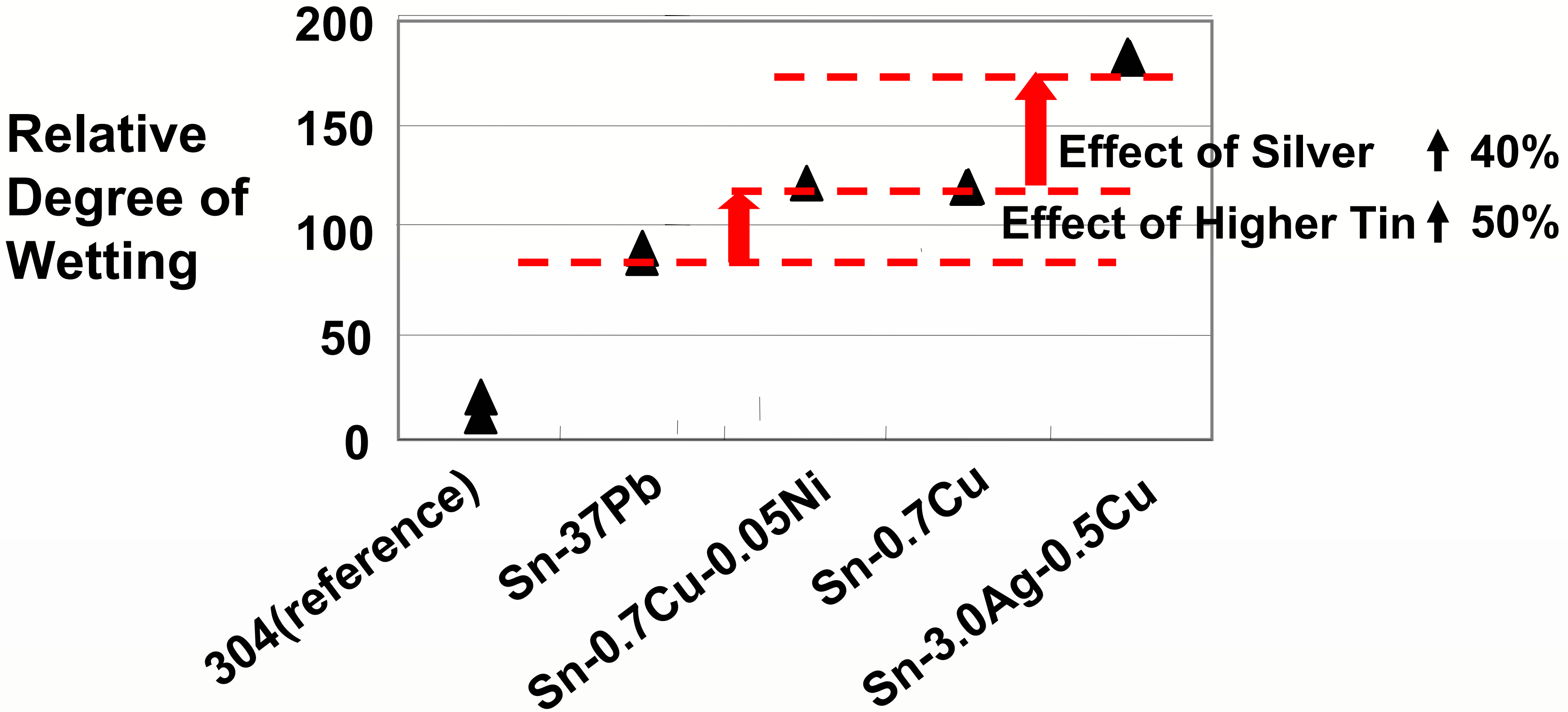


20mm Φ Area Analysed

Properties that Affect Performance in Soldering Processes

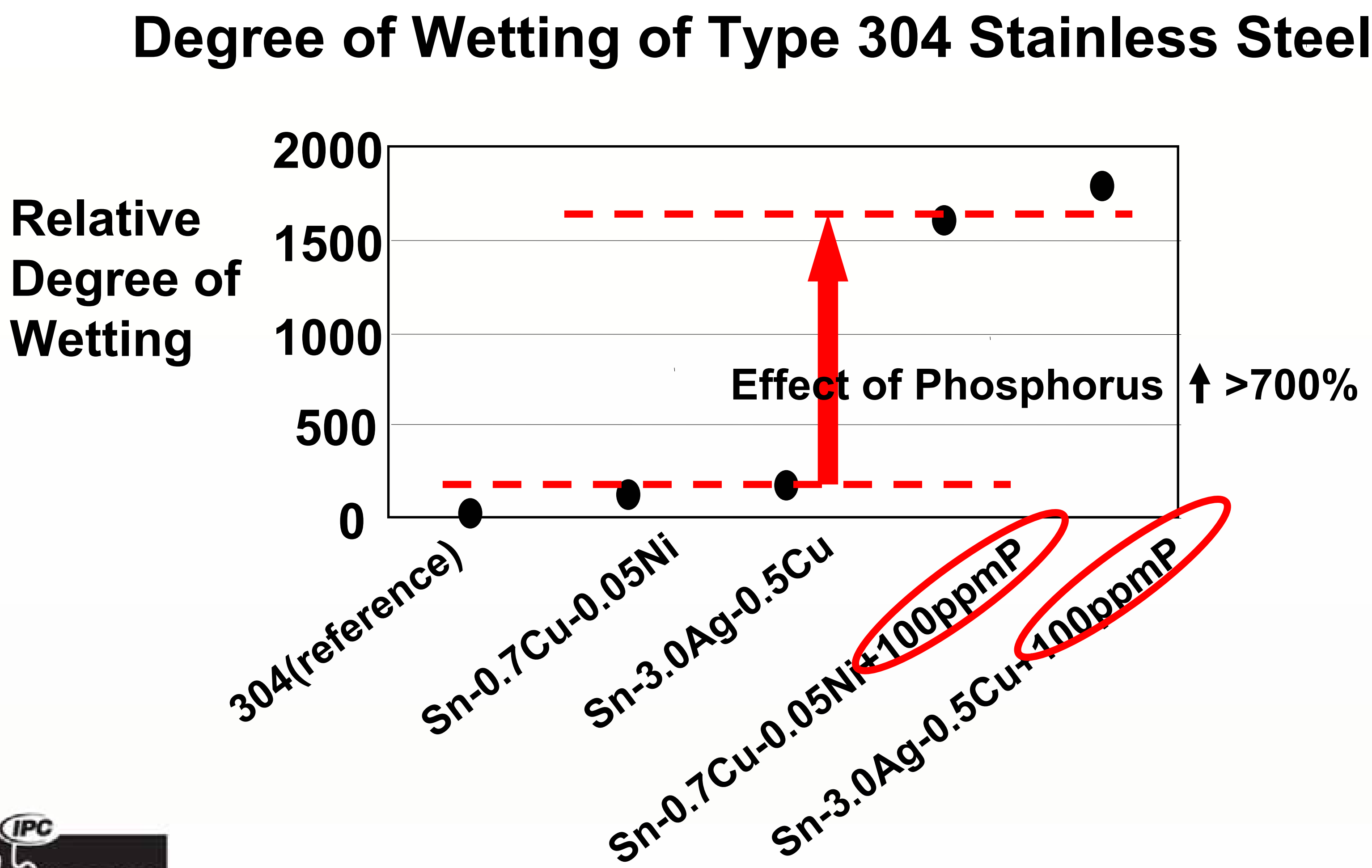
Aggressiveness Towards Stainless Steel

Degree of Wetting of Type 304 Stainless Steel



Properties that Affect Performance in Soldering Processes

Aggressiveness Towards Stainless Steel

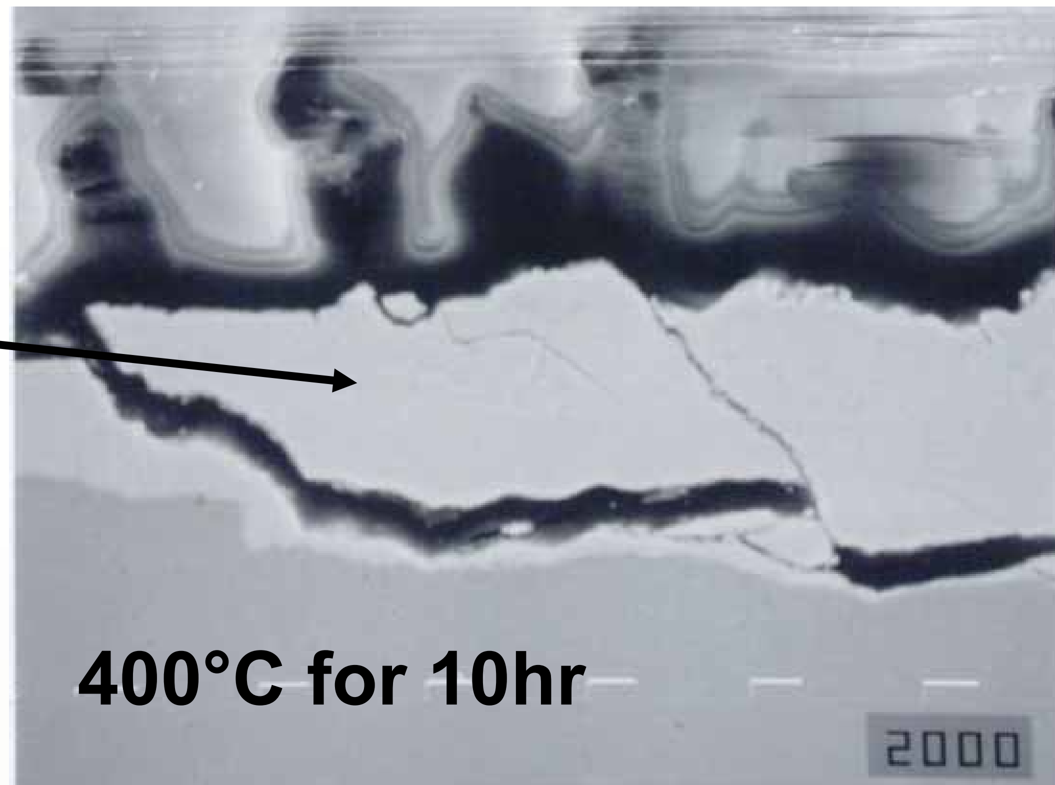


Properties that Affect Performance in Soldering Processes

Aggressiveness Towards Stainless Steel

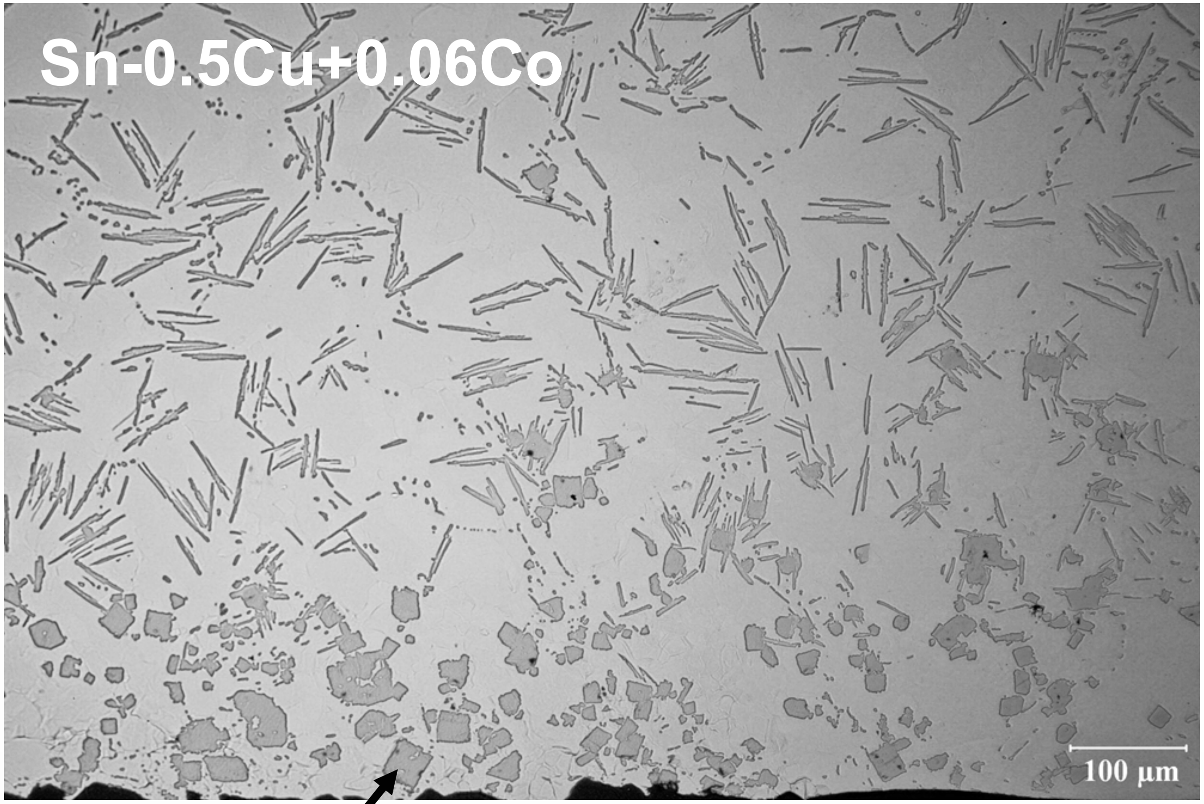
In solders containing Ag and P a thick brittle intermetallic forms that tends to spall off the surface creating opportunities for further erosion

Spalling intermetallic layer on stainless steel exposed to SAC305 with P antioxidant



Properties that Affect Performance in Soldering Processes

Stability of the molten alloy

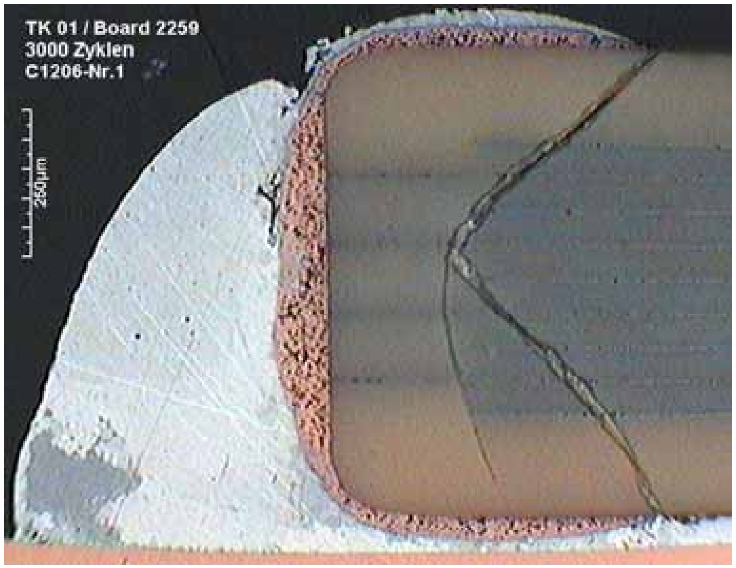


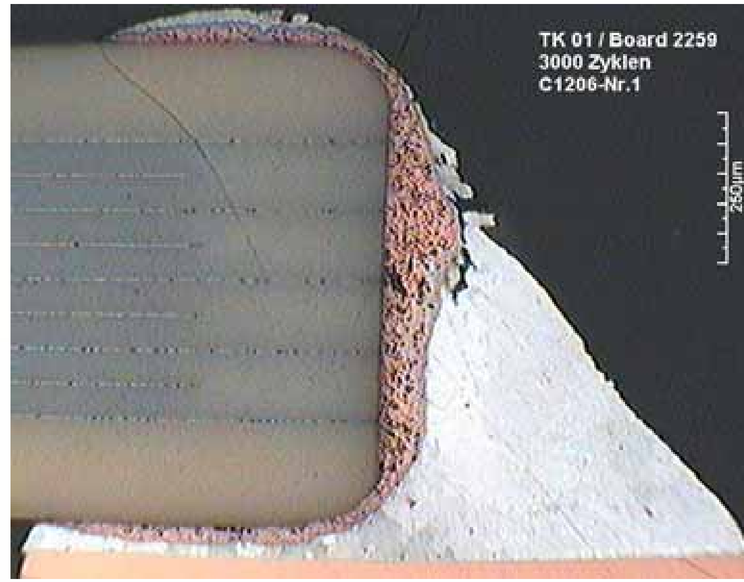
CoSn intermetallic has settled to the bottom of the crucible of molten alloy taking Co out of solution and reducing its effectiveness

Properties that Affect Performance in Service

Strength and Ductility

Sometimes a solder can be too strong

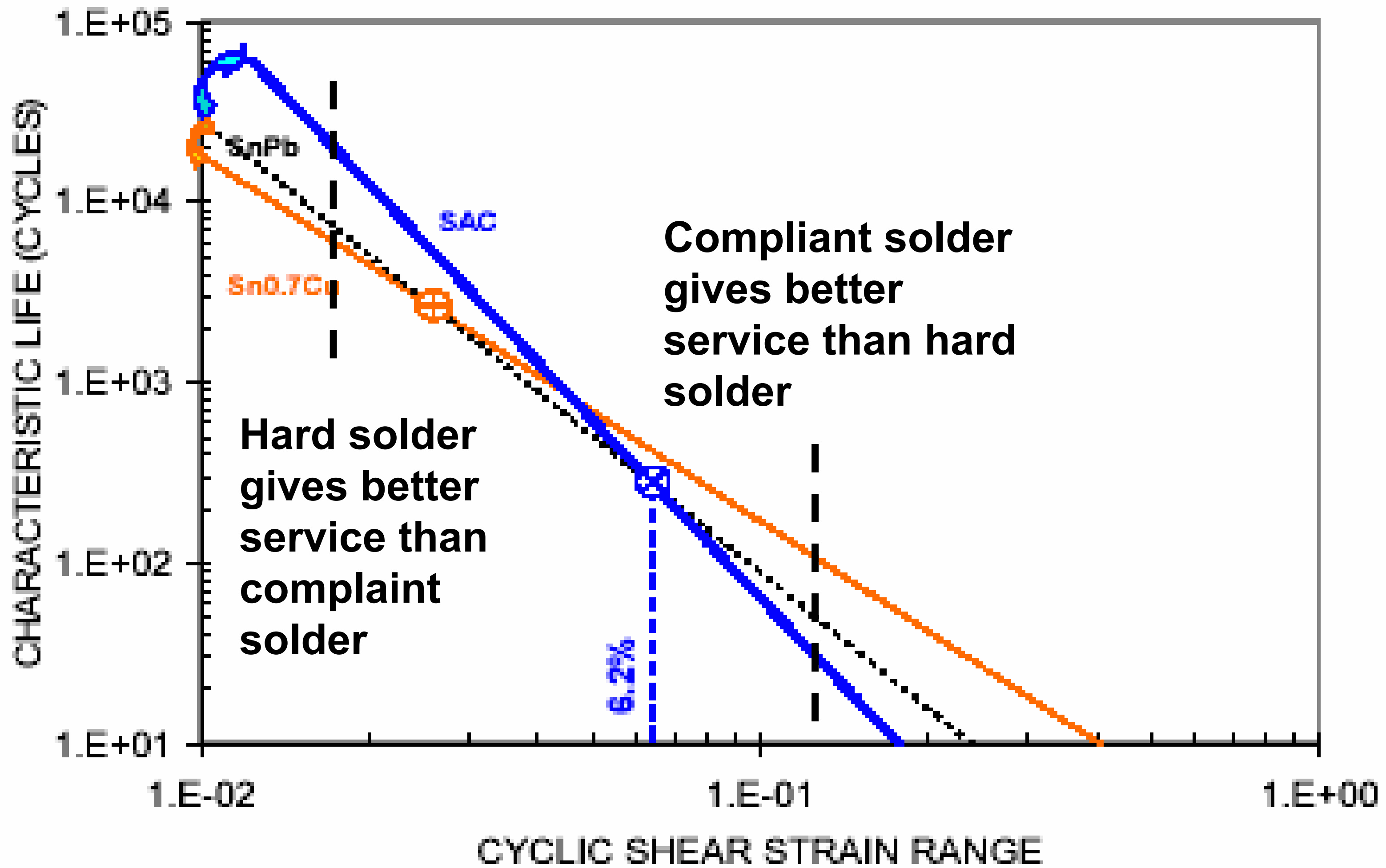




Sn-3.8Ag-0.7Cu / HAL-SnCuNi / FR4 / CMC1206:
3000 Cycles -40-+125°C

Properties that Affect Performance in Service

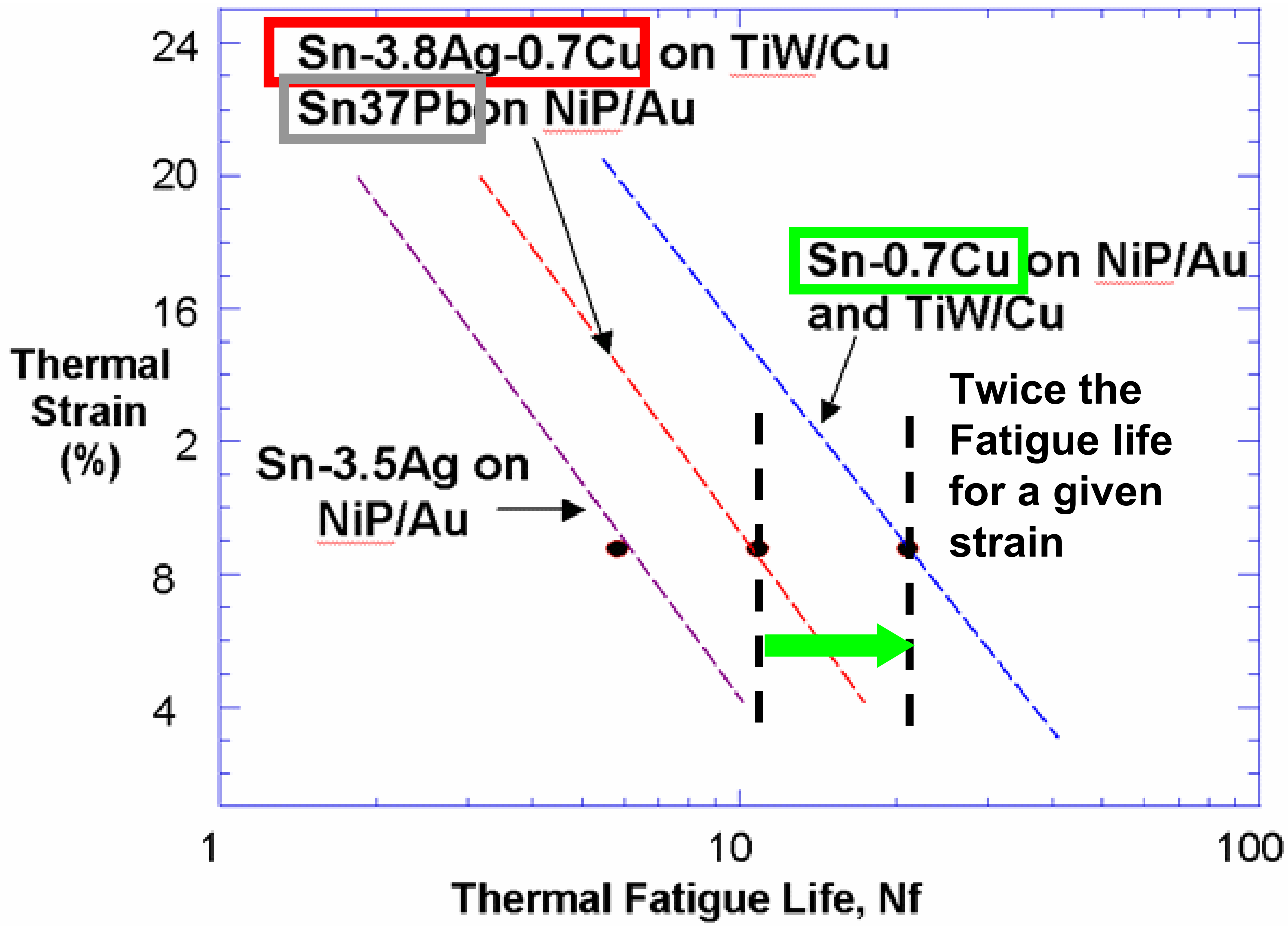
Strength and Ductility



J-P Clech IPC Printed Circuits Expo SMEMA Council APEX Designer Summit O4

Properties that Affect Performance in Service

Strength and Ductility



Data from Thermal Cycle Testing 0-100°C and -40 - +125°C

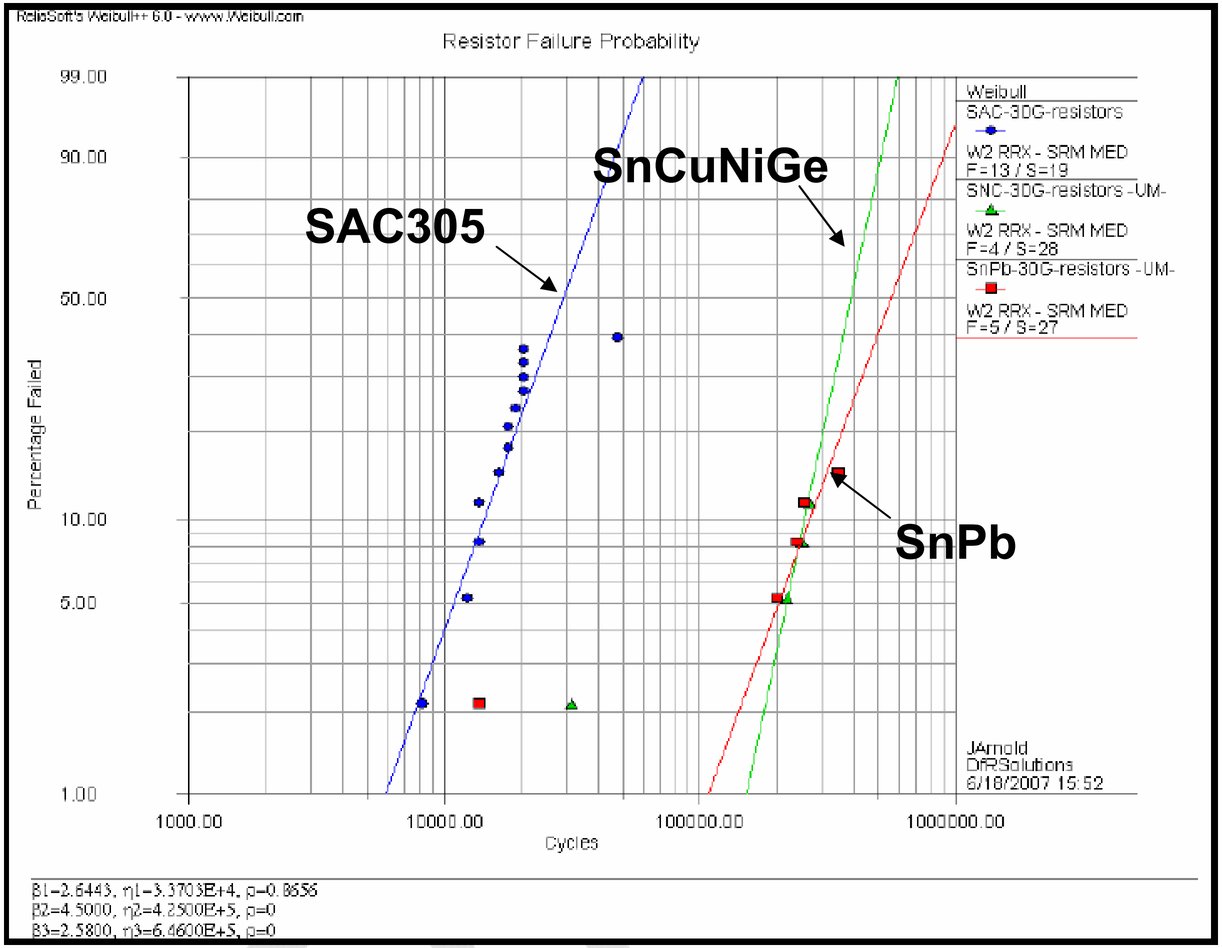
Frear et al. **JOM, 53 (6) (2001), pp. 28-32.**

Properties that Affect Performance in Service

Strength and Ductility

Vibration Testing (2512 resistor)

More ductile alloys perform better in vibration testing where the joint is subject to substantial strain



Properties that Affect Performance in Service

Impact Strength

The issue of area array packages in portable devices failing when dropped has prompted interest in the performance of alloy/finish combinations in this situation

Properties that Affect Performance in Service

Impact Strength

DAGE 4000HS Bondtester

High Speed Impact Tester

www.dage-group.com/bondtesters

Deformation Speeds

Shear: 10-4000mm/sec

Tension: 1 - 400mm/sec

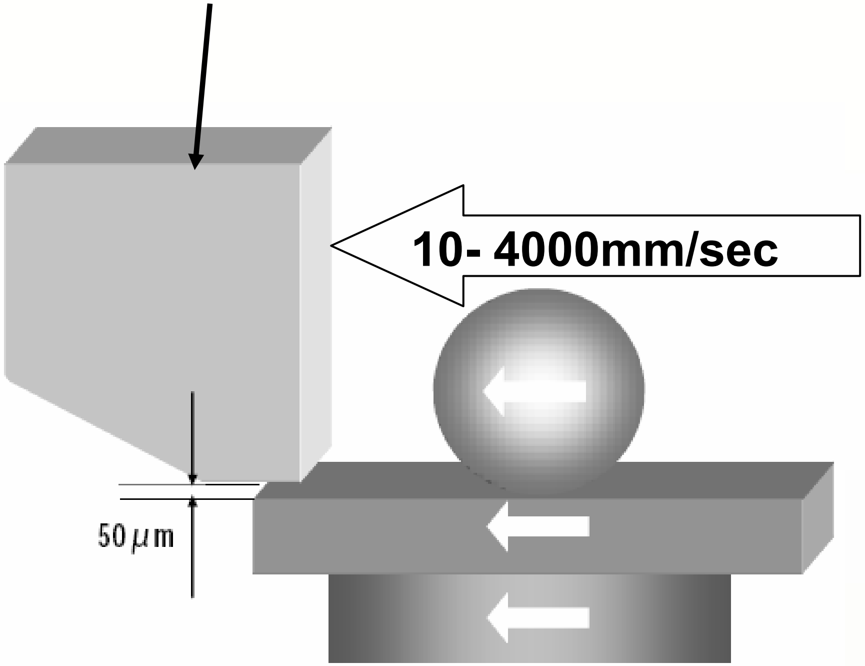
Dropped from a height of 8” → 2000mm/sec

Properties that Affect Performance in Service

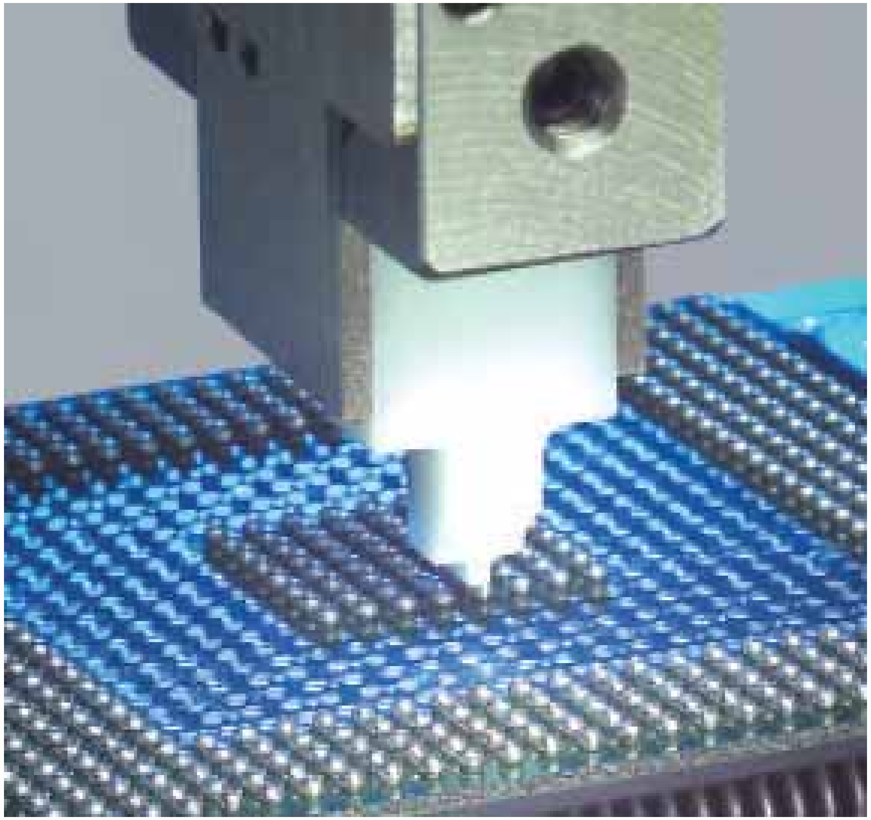
Impact Strength

In Shear

Fixed shear tool with force measurement sensor

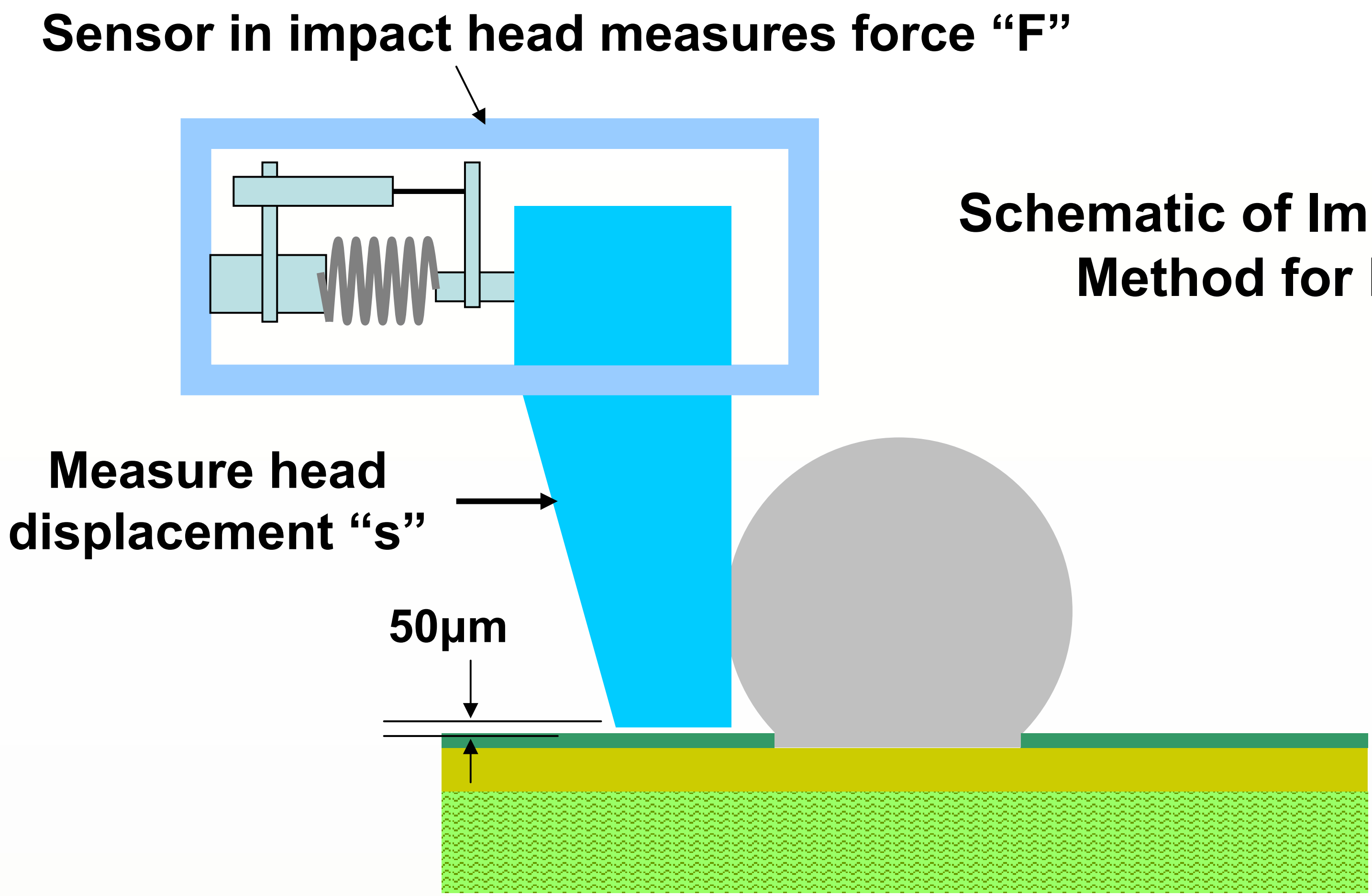


Test piece moves



Properties that Affect Performance in Service

Impact Strength

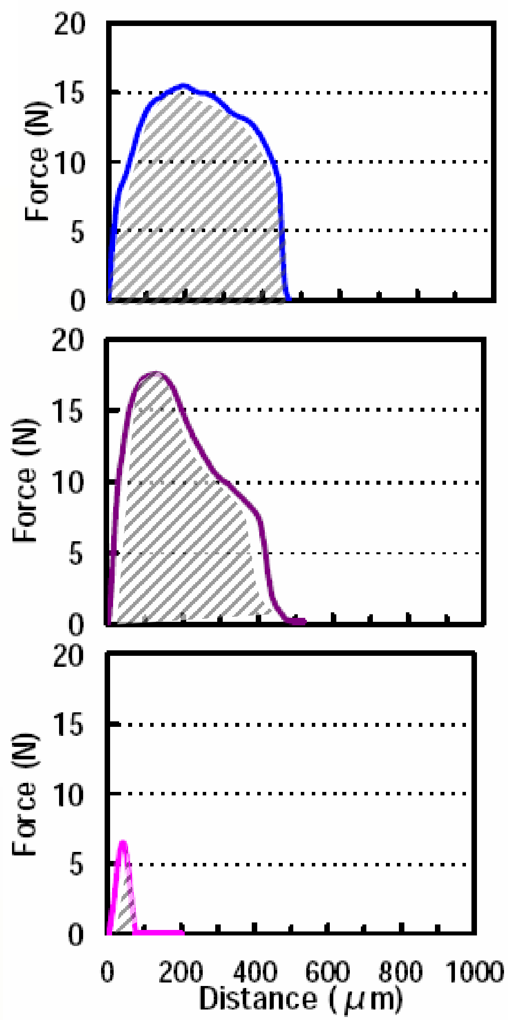


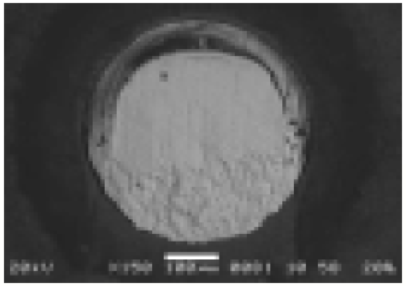
Schematic of Impact Test Method for BGA

Properties that Affect Performance in Service

Impact Strength

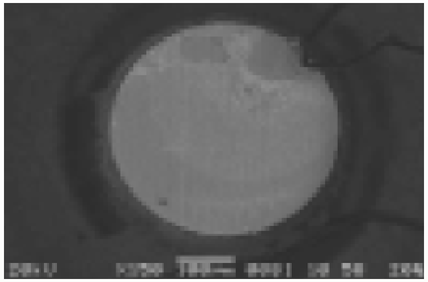
Fracture energy is the area under the force-distance plot





SAC305 10mm/sec
Completely Ductile Fracture

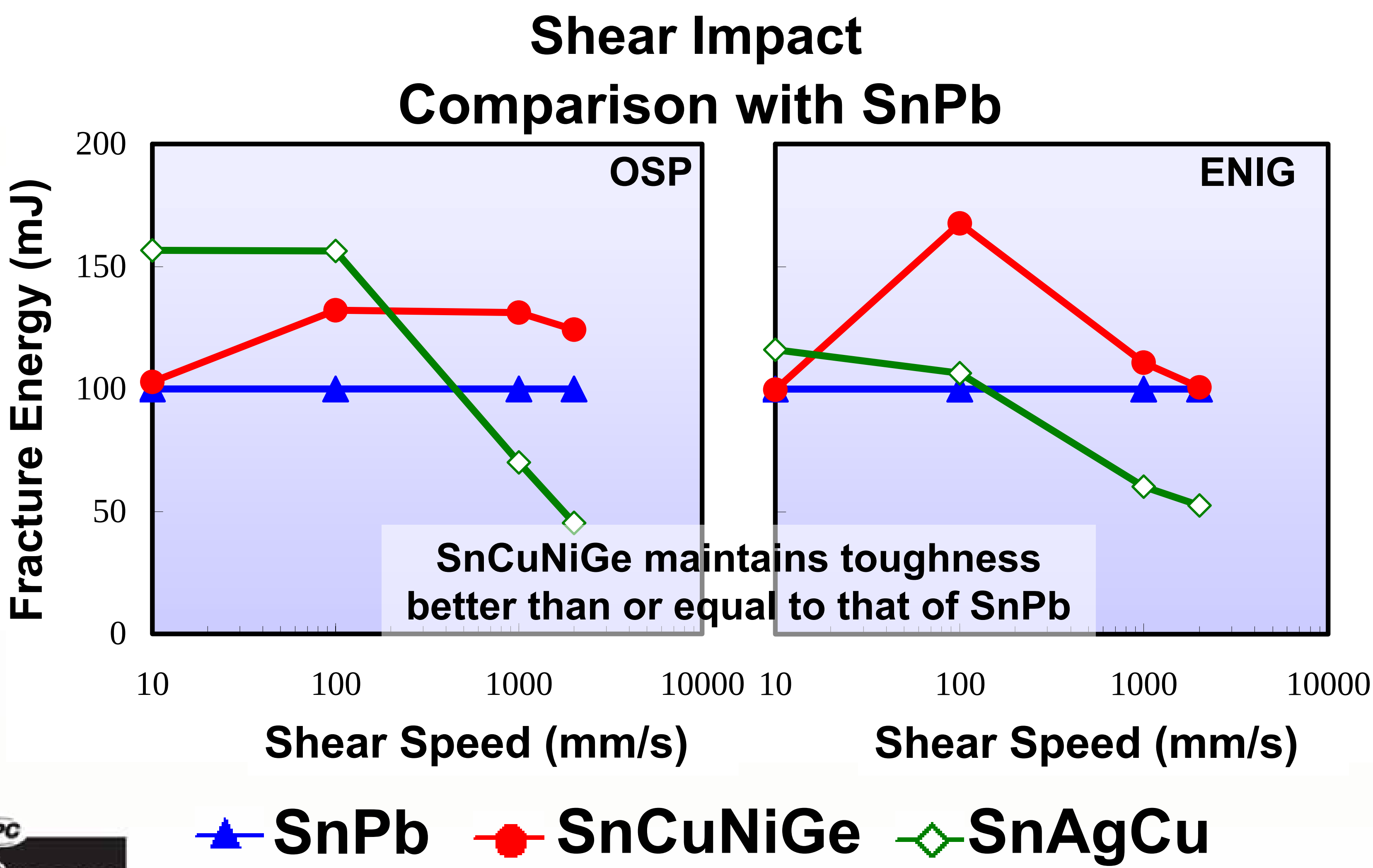
SAC305 100mm/sec
Mixed Mode Fracture



SAC305 1000mm/sec
Completely Brittle Fracture

Properties that Affect Performance in Service

Impact Strength

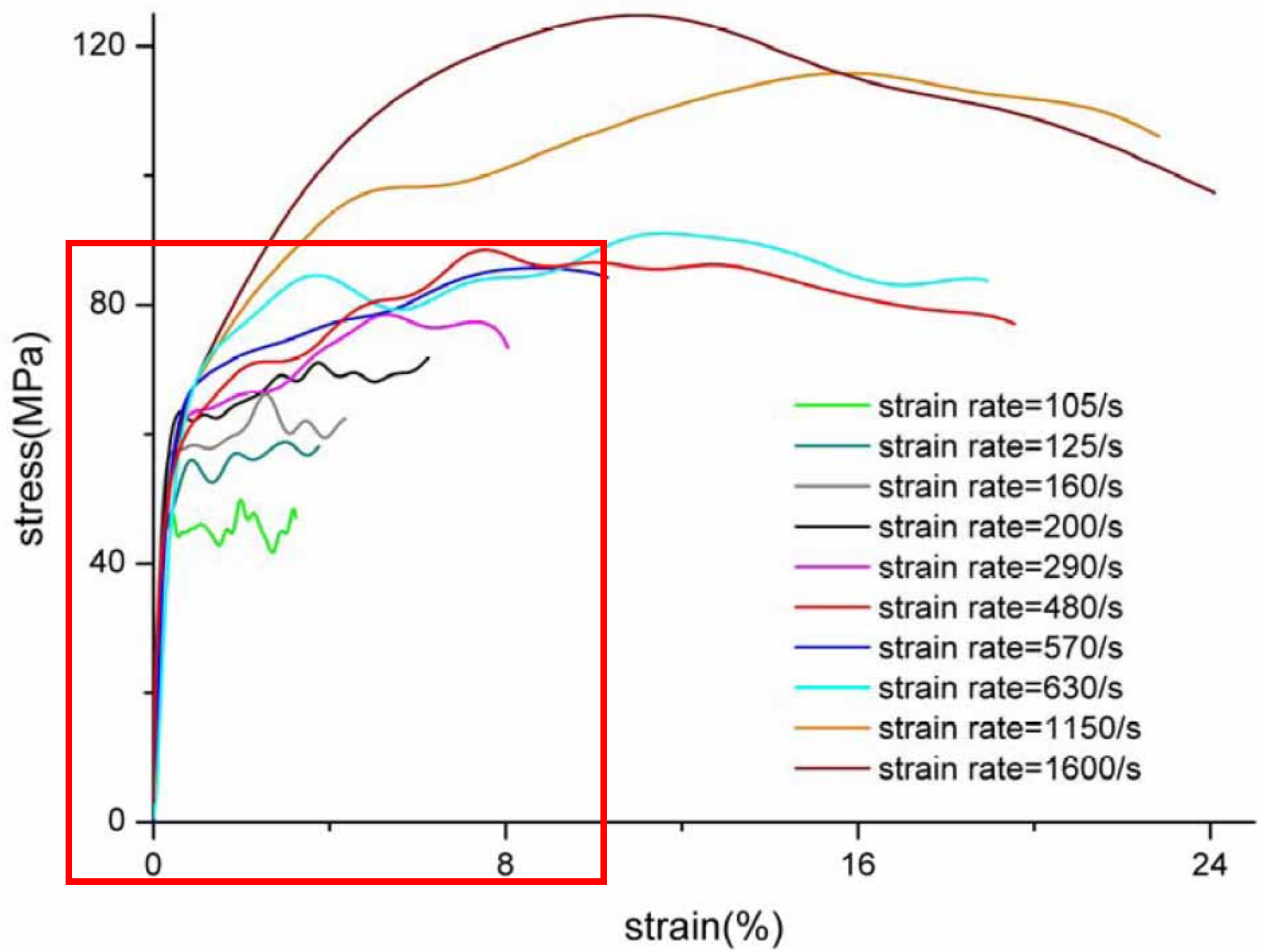


Properties that Affect Performance in Service

Impact Strength

What determines the fracture mode in impact testing?

Strain rate sensitivity of shear stress?

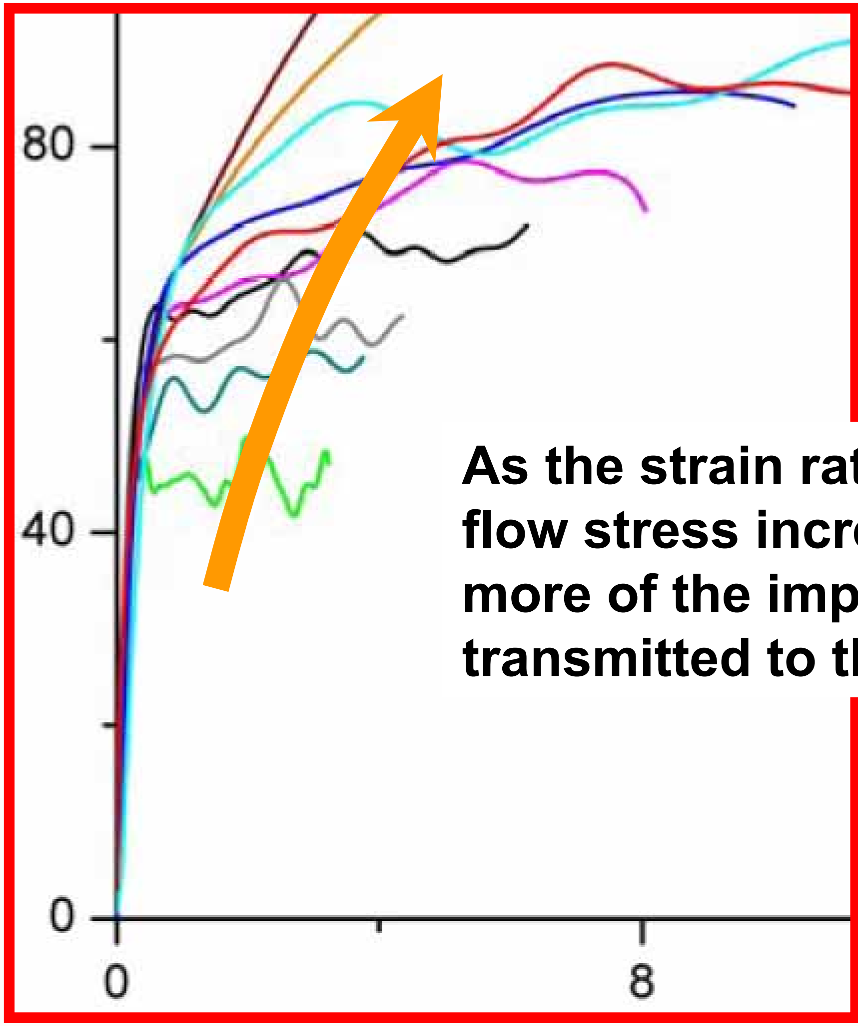


Xu et al. IPC/JEDEC Conference, Austin TX, December 2008

Properties that Affect Performance in Service

Impact Strength

Strain rate sensitivity of shear stress



As the strain rate increases the flow stress increases and more of the impact load is transmitted to the interface

Xu et al. IPC/JEDEC Conference, Austin TX, December 2007

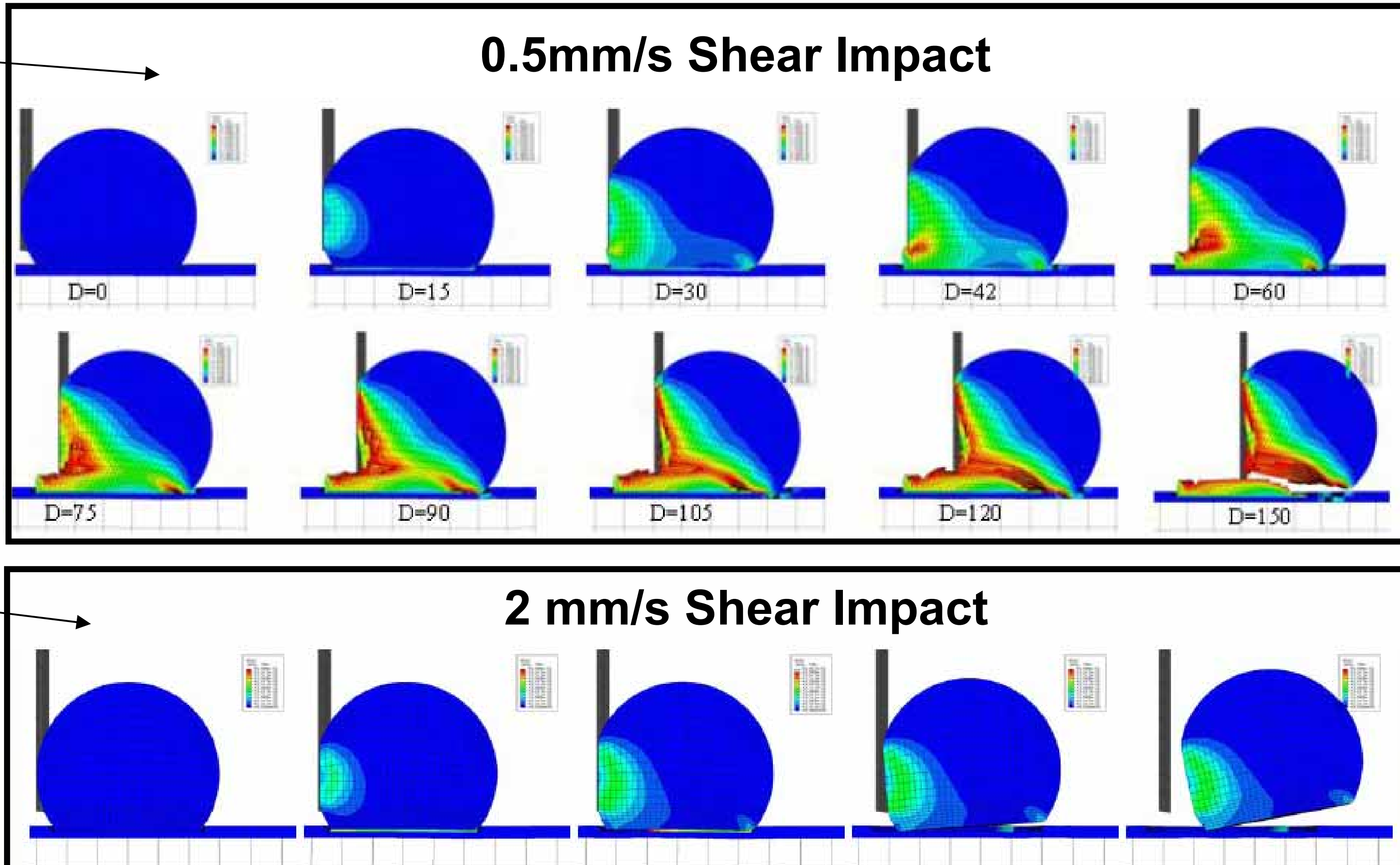
Properties that Affect Performance in Service

Impact Strength

Strain Distribution during Impact Loading

Plastic strain throughout the sphere means that stresses are more widely spread

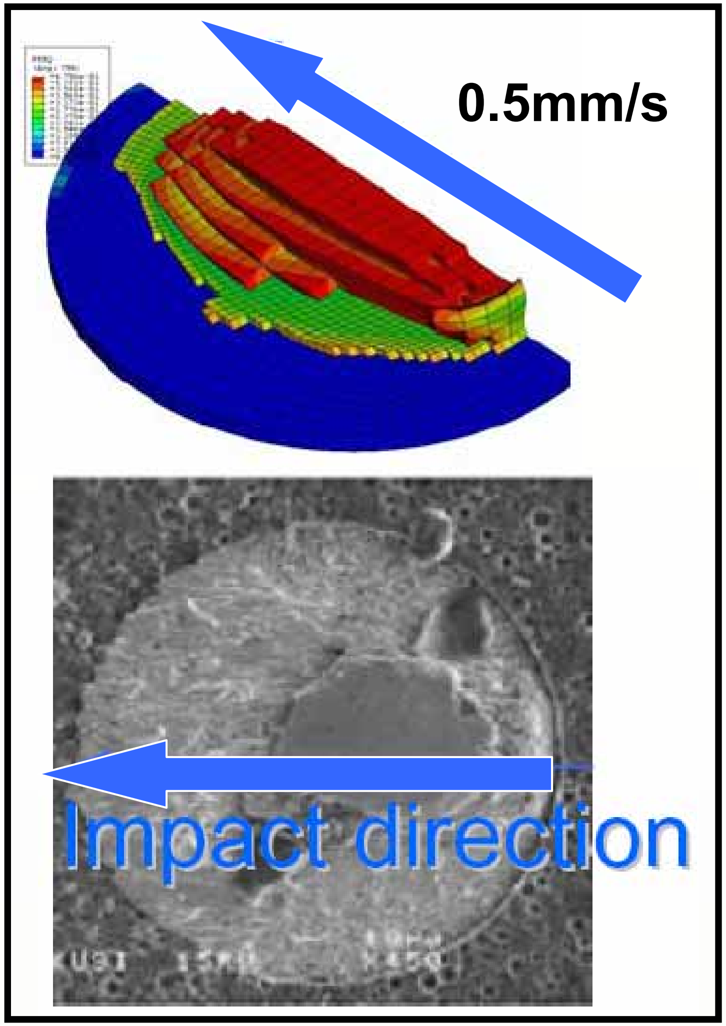
Strain is limited by the high flow stress at this strain rate. Stress is widespread

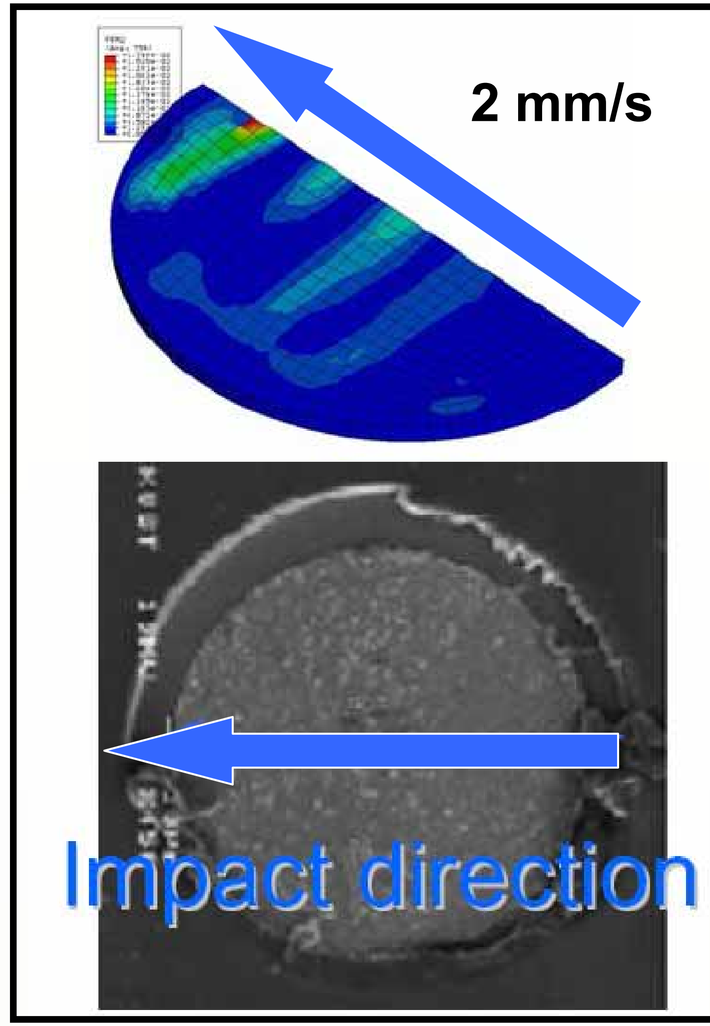


Xu et al. IPC/JEDEC Conference, Austin TX, December 2007

Properties that Affect Performance in Service

Impact Strength



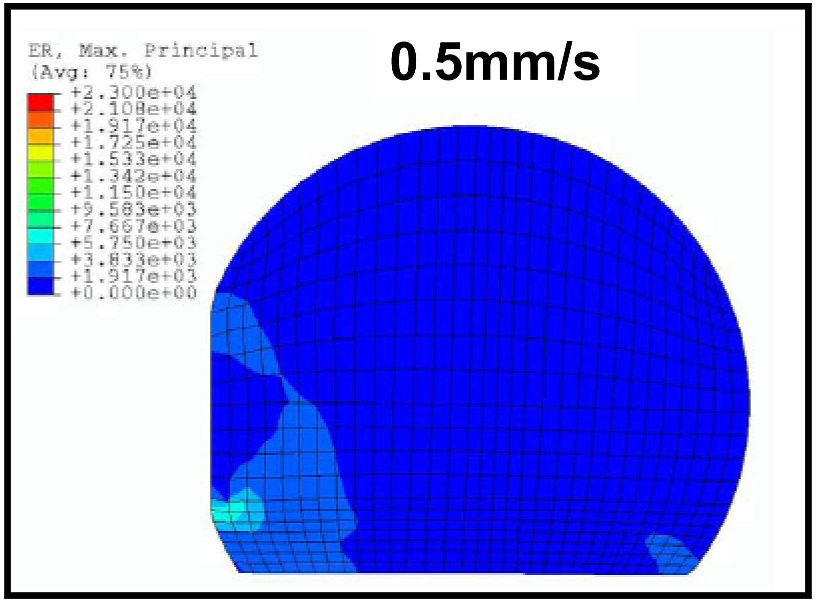


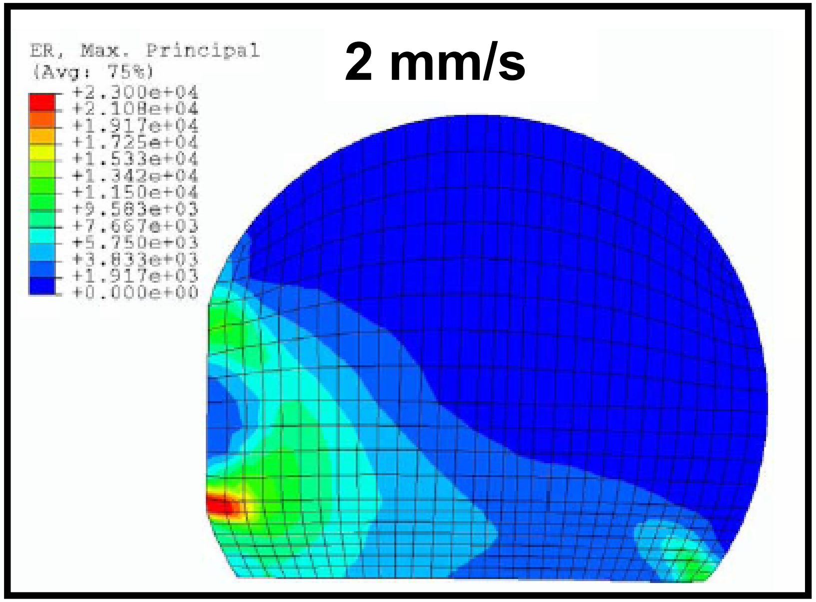
Xu et al. IPC/JEDEC Conference, Austin TX, December 2007

Properties that Affect Performance in Service

Impact Strength

Strain RATE Distribution in 3mm SAC105 Solder Sphere Shear Impact Loading





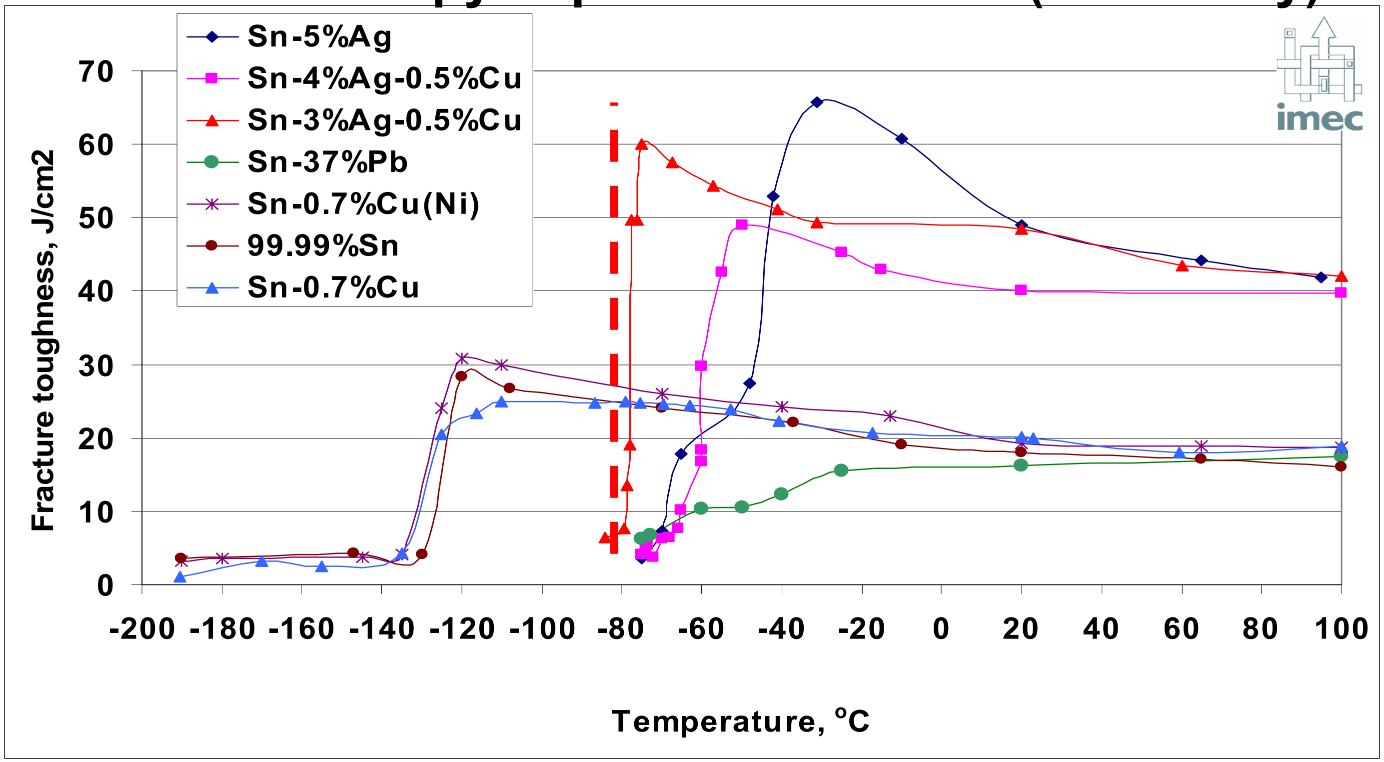
- **In an alloy with a high strain rate sensitivity of flow stress a high strain rate is transmitted to the solder substrate interface**
- **Brittle failure at the interface is likely even if there is not an excessive intermetallic layer**

Xu et al. IPC/JEDEC Conference, Austin TX, December 2007

Properties that Affect Performance in Service

Impact Strength

Solder alloys can have different impact strengths at very low temperatures



Ratchev et al., EMPC 2005 (IMAPs-Europe), June 12-15, Brugge, Belgium.

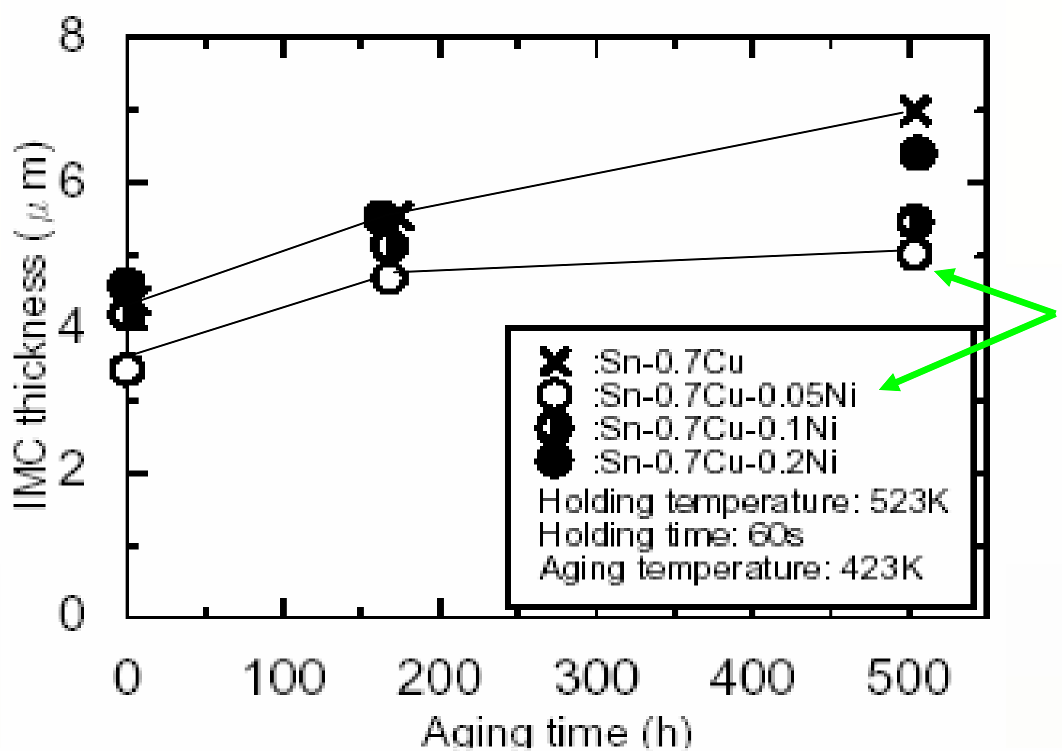
Properties that Affect Performance in Service

Intermetallic Growth

The rate of growth of the intermetallic at the solder/substrate interface can affect reliability, particularly under conditions of impact loading

The rate of intermetallic growth can be controlled by microalloying additions

Minimum growth rate occurs in the Sn-0.7Cu alloy when Ni at a level of ~0.05%

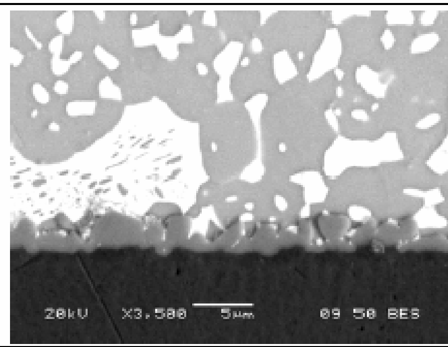
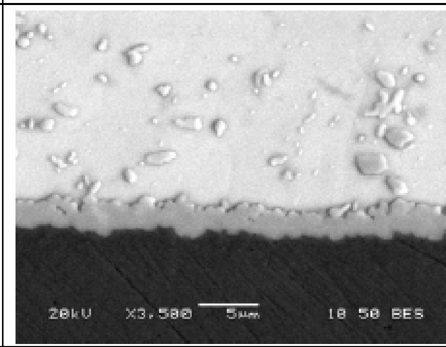
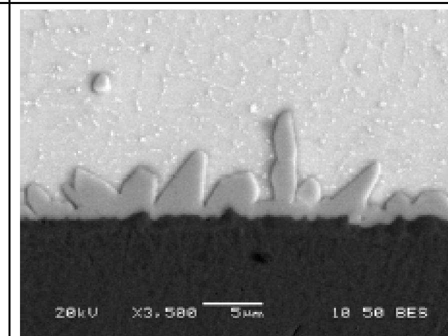
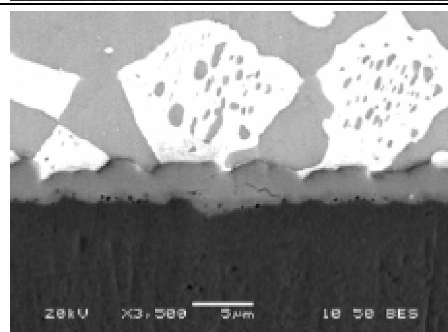
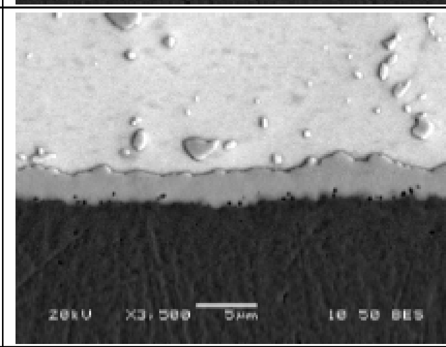
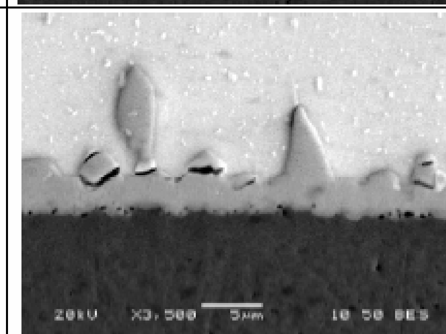


Nishikawa et al.,Soldertec/IPC Lead-free Conference Amsterdam, June 2004

Properties that Affect Performance in Service

Intermetallic Growth

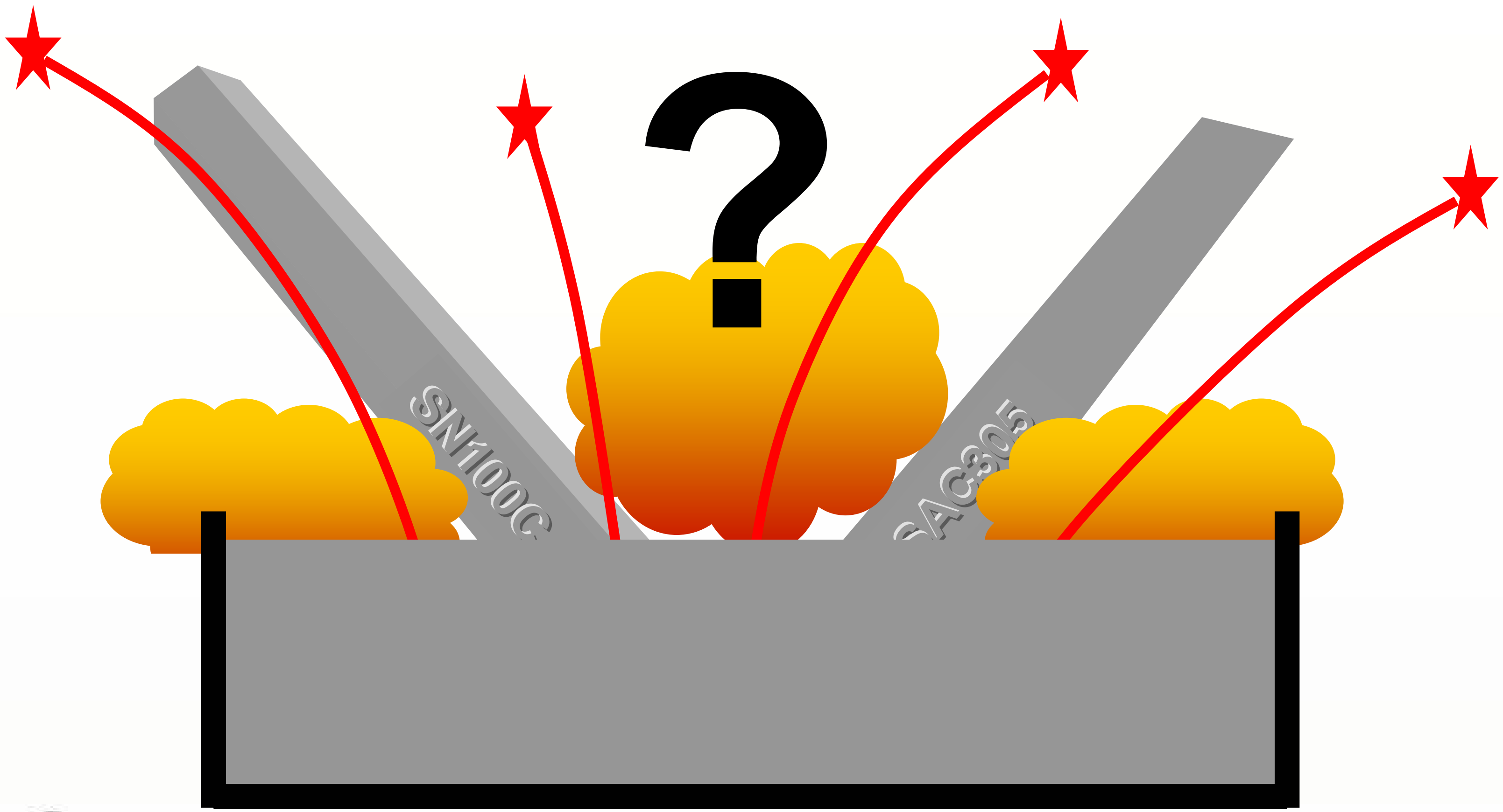
The rate of growth of interfacial intermetallic varies with the alloy

	Sn-37Pb	**SnCuNiGe**	Sn-3.0Ag-0.5Cu
Initial			
Reflowed Twice +500 at125°C			

Properties that Affect Performance in Service

Compatibility with Other Lead-free Solders

What Happens if You Mix Different Lead-free Solders in An Assembly?



Compatibility with Other Lead-free Solders

The first step in evaluating the reliability of a mixed solder joint is to consider the possible combinations of elements that might occur.

There will usually be sufficient data available to make a reasonable prediction of likely properties.

There are no surprises in the most likely mixed systems

Example of Possible Mixed Alloy System

Alloy	Constituent Elements						
	Sn	Cu	Ag	Ni	Ge	Bi	Co
SAC305	96.5	0.5	3.0	0.00	0.000	0.00	0.00
Alternative A	99.2	0.7	0.0	0.06	0.006	0.00	0.00
75:25 Mix	97.2	0.6	2.3	0.02	0.002	0.00	0.00
50:50 Mix	97.9	0.6	1.5	0.03	0.003	0.00	0.00
25:75 Mix	98.6	0.7	0.8	0.05	0.005	0.00	0.00

These mixed alloys will have properties that range between those of "SAC" and "LowSAC". These alloys have an established record of reliability

Compatibility with Other Lead-free Solders

The following combinations were examined in a study done by Nihon Superior:

Hand Soldering (Tip Temperature: 280 ° C Contact Time: 2 seconds)				
	Alloy	Sn-0.7Cu+Ni	Sn-3.0Ag-0.5Cu	Sn-37Pb
	Flux	3% NS 020[1]	3% NS 020[1]	NS 110MS[2]
	Wire Diameter	0.6mm	0.6mm	0.8mm
Wave Solder Alloy	Sn-0.7Cu+Ni	X	X	X
	Sn-3.0Ag-.5Cu	X	X	X
	Sn-37Pb	X	X	X

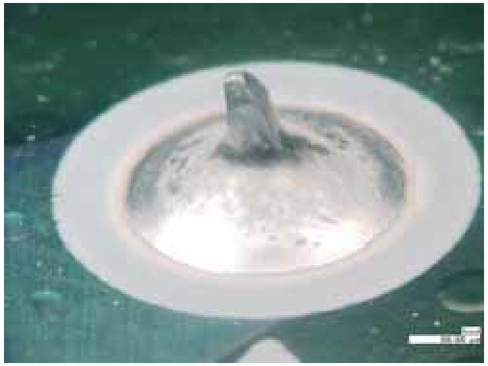
Properties that Affect Performance in Service

Compatibility with Other Lead-free Solders

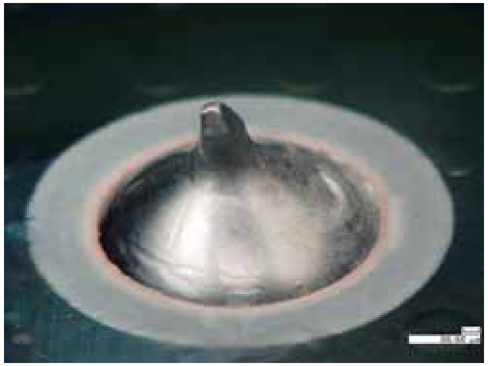
Example Study

Wave solder with Sn-3.0Ag-0.5Cu, Hand Solder with Sn-0.7Cu-0.06Ni-0.006Ge

After hand soldering with SN100C the shrinkage cavity disappeared



After Wave Soldering



After Hand Soldering

After thermal cycling the surface of the solder fillet became grainy but there was no cracking

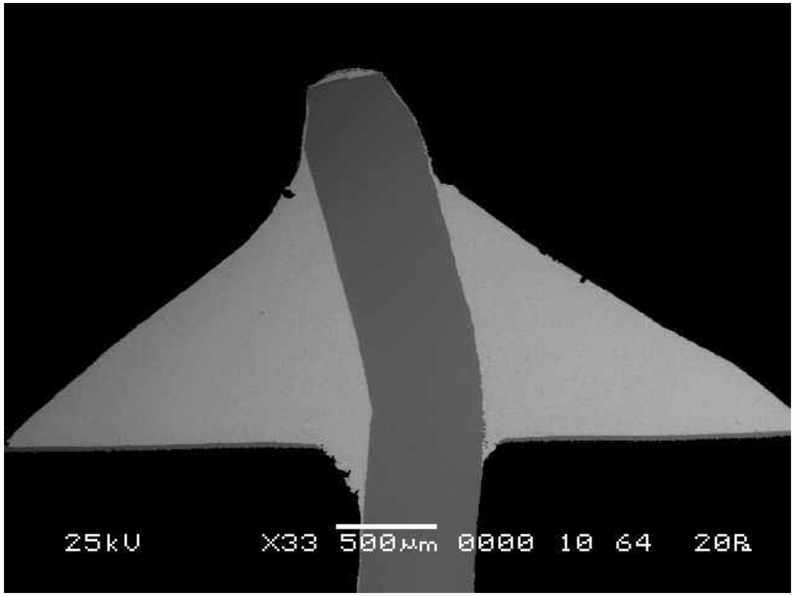
After 500 Thermal Cycles

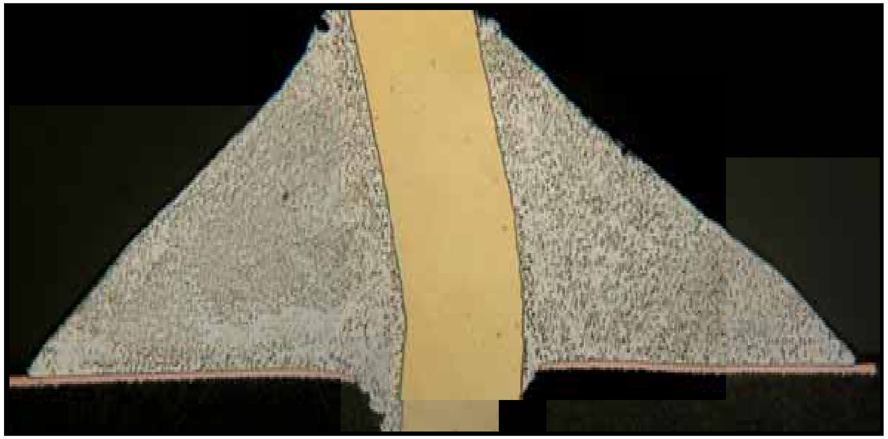
After 1,000 Thermal Cycles

Properties that Affect Performance in Service
Compatibility with Other Solders

Wave solder with Sn-3.0Ag-0.5Cu, Hand Solder with Sn-0.7Cu-0.06Ni-0.006Ge

After 1000 cycles





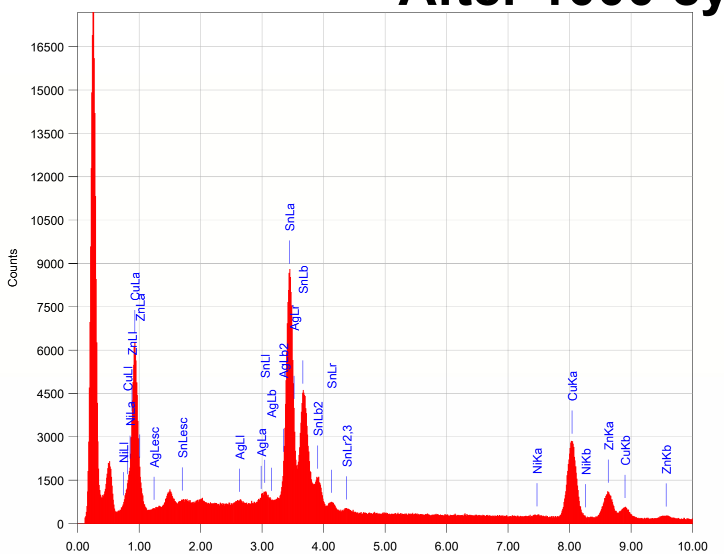
No defects

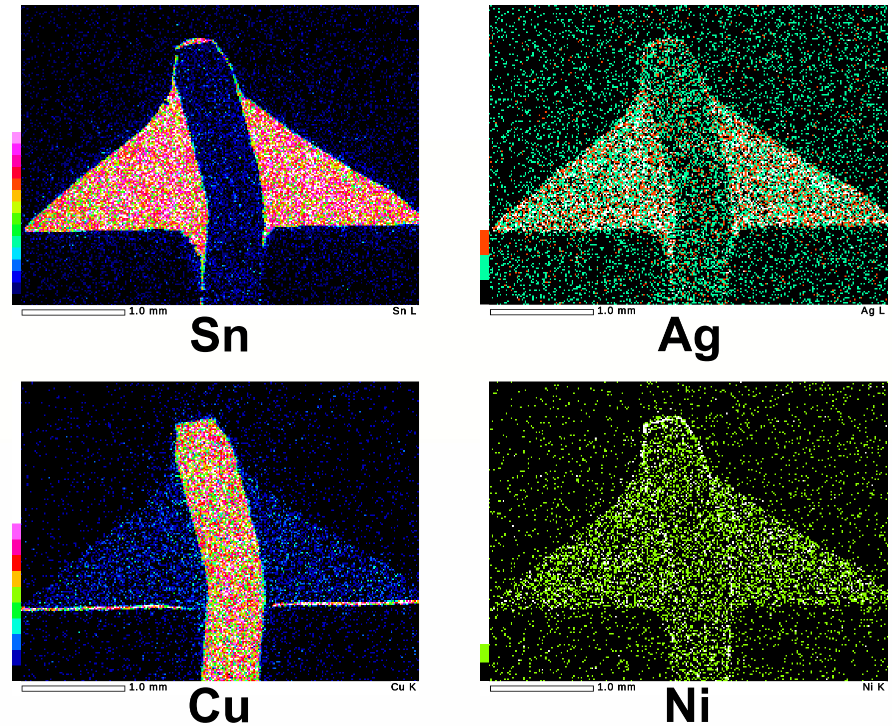
Properties that Affect Performance in Service

Compatibility with Other Solders

Wave solder with Sn-3.0Ag-0.5Cu, Hand Solder with Sn-0.7Cu-0.06Ni-0.006Ge

After 1000 cycles





Element	(keV)	Mass%	Tolerance%	Atomicity%
Cu K	8.040	31.79	1.64	41.58
Ag L	2.983	2.43	0.96	1.88
Sn L	3.442	47.41	1.12	33.19

Segregation and the resulting inhomogeneity in the microstructure can be a cause of loss of reliability.

The reliability of these mixed solder joints has not been compromised by such inhomogenity

OBJECTIVE

To provide a framework in which candidate lead-free solders can be assessed for the suitability as replacements for Sn-37Pb

<u>Properties that Affect Performance in Soldering Processes</u>

- **Melting point**
- **Wetting properties**
- **Solidification mode/Fluidity/Drainage**
- **Aggressiveness towards copper**
- **Aggressiveness towards soldering equipment**
- **Stability of the molten alloy**

<u>Properties that Affect Performance in Service</u>

- **Strength and ductility**
- **Impact strength**
- **Microstructure**
- **Stability of microstructure/ Intermetallic growth**
- **Reliability**

Properties that are Important in a Lead-free Solder

CONCLUSIONS

Melting Point

Since lead-free solders seldom freeze at their theoretical melting point and since the amount of superheat needed to ensure fluidity at temperatures close to the melting point varies the melting point is not always the most important factor affecting process temperatures.

Wetting Properties

When comparing wetting properties in a wetting balance test allowance should be made for the time it takes to heat the test piece. That factor can be allowed for in setting processes parameters in production soldering.

Solidification Mode

The way in which an alloy solidifies can have a major effect on its behavior in soldering processes and on the microstructure of the solder joint. Reliability as well as joint appearance can be affected by the joint microstructure. There is a substantial variation in the solidification behavior of currently available lead-free solders and this can be a factor in alloy selection.

CONCLUSIONS (continued)

Copper Erosion can have a significant effect on production yields and the reliability of electronics assemblies in service. There is a substantial variation in the aggressiveness towards copper of currently available lead-free solders

Erosion of Soldering Equipment can have a significant effect on capital and operating costs of electronic production. There is a substantial variation in the aggressiveness towards copper of currently available lead-free solders

Stability of the Molten Solder

The intermetallic phases in lead-free alloy systems have high melting points and can precipitate out to leave the remaining alloy depleted in key alloying element.

Strength and Ductility

Service conditions for a lead-free solder have to be reviewed to determine whether a high yield point or high ductility is the most appropriate property for long service life and the alloy selected accordingly. In situations where the joint has to accommodate substantial strain ductility is the more important property. Tin-lead solder is a very ductile.

CONCLUSIONS (continued)

Impact Strength

A key consideration for all portable devices. While interfacial intermetallics are a factor possibly more important is the strain rate sensitivity of flow stress.

Microstructure/Stability of Microstructure/Intermetallic Growth

The ideal microstructure is a homogeneous distribution of finely dispersed phases to ensure even strain distribution and a minimal smooth intermetallic at the solder/substrate interface

Reliability

Reliability in service is the result of the sum total of many properties each of which have to be optimized for the particular application. Because of the great variation in service conditions to which electronics assemblies are now exposed it might not be appropriate to specify a single solder for all applications.

Properties that are Important in a Lead-free Solder

MAJOR CONCLUSION

Don't Panic

- Embrace enthusiastically the opportunities created by the new alloys that have been developed in response to the challenge to go lead-free.
- Take advantage of the great increase in the understanding of solders and soldering technology that has been triggered by the move to lead-free.

Have Fun