Strength of Lead-free BGA Spheres in High Speed Loading

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ABSTRACT

Concern about the failure of lead-free BGA packages when portable devices such as cell phones are accidentally dropped and a general concern about the resistance of these packages under shock loading has prompted an interest in the impact strength of the soldered BGA connection. This paper reports the results of the measurement of the impact strength of lead-free 0.5±0.01mm diameter BGA spheres on 0.42mm solder mask defined pads on copper/OSP and ENIG substrates using recently developed equipment that can load individual BGA spheres at high strain rates in shear and tension. Impact strength is measured as the energy required to detach the sphere from the substrate to which it has been soldered. Two lead-free solders, Sn-3.0Ag-0.5Cu and a silver-free Sn-0.7Cu-0.05Ni-0.006Ge were studied with Sn-37Pb included as a benchmark. To study the effect of intermetallic growth on impact strength BGA were tested after up to two reflow cycles and 200 hours ageing at 150°C. BGA were tested in shear at speeds of 10, 100, 1000, 2000 and 4000mm/sec and in tension at speeds of 1, 10, 100, 200, and 400mm/sec. Fracture surfaces were studied using scanning electron microscopy and the relative amounts of ductile and brittle fracture noted. Spheres were cross-sectioned to observe the effect of ageing on the growth of interfacial intermetallic. While at load rates lower that about 100mm/sec in shear and 10mm/sec in tension the energy required to detach the SnAgCu was higher than that required to detach the Sn-Pb or SnCuNiGe sphere, at higher speeds the SnAgCu failed in a brittle manner at low impact energy while the SnCuNiGe alloy required more energy even than the Sn-Pb and exhibited a high proportion of ductile fracture. This difference between the SnAgCu and the SnCuNiGe alloy increased after ageing and this could be correlated with the greater increase in the thickness of the intermetallic layer in the SnAgCu.

Key words: BGA spheres, impact testing, lead-free solder

INTRODUCTION

As lead-free solders have moved from the laboratory to the production floor and then into field service an unanticipated issue that has emerged has been the greater vulnerability of "the lead-free alloy of choice for the electronics industry"[1], Sn-3.0Ag-0.5Cu ("SAC305) to the sort of shock loading that occurs when a portable device such as a cell phone is dropped onto a hard surface.

Since much of the work on the selection of lead-free solders was done before portable devices were as widely used as they are now the industry could be forgiven for not giving sufficient consideration to this aspect of solder performance when the default lead-free solder was selected. And the fact that the strength of the SAC305 alloy at moderate strain rates is much greater than that of the Sn-37Pb alloy that it is replacing provided some basis for expecting that the alloy would prove superior to tin-lead solder in all situations. The potential problem was realised fairly early in the implementation of lead-free soldering [2] but the industry stayed with SAC305 as the default alloy in all situations.

Quite early in the implementation of lead-free soldering some researchers realised that the basic tin-copper eutectic alloy, nominally Sn-0.7Cu, could be a better choice than SnAgCu alloys in at least some applications because of its higher ductility [3]. During the more than half a century when virtually all electronics was assembled with tin-lead solder of close to eutectic composition the ductility of that alloy was one of its under-appreciated properties.

Even before the potential of the problem was fully realised some researchers had started to investigate the possibility of increasing the toughness of SnAgCu alloy joints by the use of low level quaternary additions [4] that appeared to work through their effect on the interfacial intermetallic compound. However, as Frear et al. pointed out [2], another alternative is to use the basic tin-copper eutectic alloy.

In fact Sn-0.7Cu is one of the alloys that had been recommended by industry consortia as a low cost lead-free solder but it was not widely used because "The results with SnCu0.7 were generally unacceptable, showing poor joint fillet shape and the high temperatures/times needed to effect soldering caused deterioration of the board materials." [5].

However, the discovery that the properties of the Sn-0.7Cu alloy as a solder could be greatly enhanced by an addition of nickel at a low but quite specific level [6] opened the possibility of its wider use in commercial mass production. An alloy based on the Sn-Cu-Ni system with the further addition of Ge is now one of the alloys most widely used in lead-free wave soldering [7] and its performance in production and reliability in service [8] has prompted its evaluation in other soldering applications.

This paper reports a preliminary study to determine whether the Ge-enhanced, Ni-modified Sn-07Cu solder offers any advantage over SAC305 in high strain rate testing.

TEST VEHICLE

Pads for the attachment of the candidate solders were created on copper-clad laminate that had either an OSP or ENIG finish (Table 1) by using solder mask.

Table 1. Substrate for BGA attach.

Laminate	FR4
Thickness	1.6mm
Solder Mask Defined Pad	0.42±0.02mm
Finish	OSP
	ENIG: 0.3µm Ni/0..03µmAu
Resist Thickness	30-40µm

Three alloys with the compositions listed in Table 2 were fabricated into 5±0.01mm diameter solder spheres using a liquid drop extrusion method..

Table 2. Alloys evaluated

Code	Composition (mass %)
SnPb	Sn-37Pb
SnCuNiGe	Sn-0.7Cu-0.05Ni-0.006Ge
SnAgCu	Sn-3.0Ag-0.5Cu

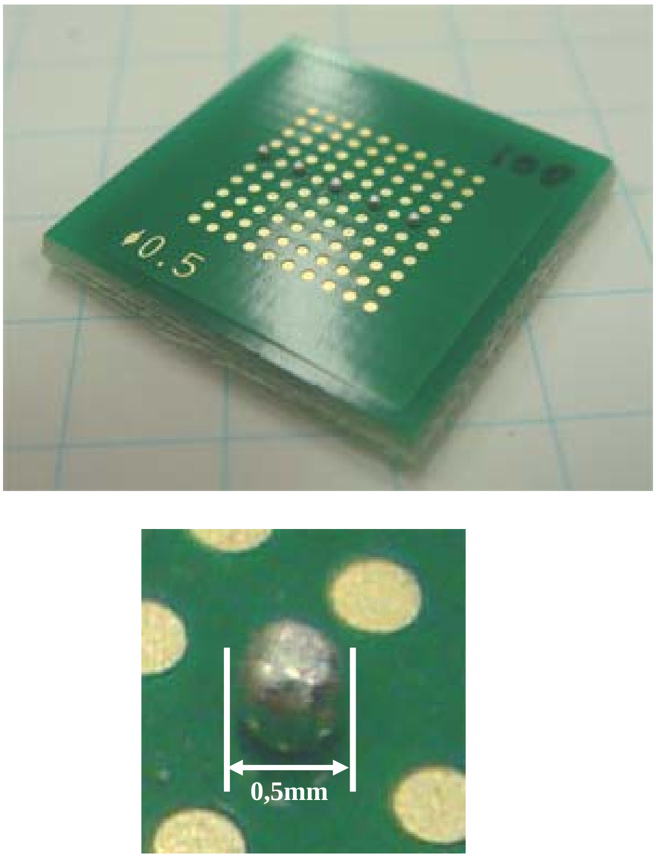


Figure 1. Test Vehicle

The pads of the test vehicle were fluxed with an activated rosin flux and the solder spheres placed and reflowed with the thermal profiles listed in Table 3

Table 3. Reflow profiles for solder spheres

Alloy	Peak Temperature	Time Above Liquidus
SnPb	230°C	40sec>210°C
SnCuNiGe	240°C	40sec>220°C
SnAgCu	240°C	40sec>220°C

To determine the effect of further thermal exposure on impact properties test pieces were subject to the additional ageing conditions listed in the second and third rows of Table 4.

Table 4. Ageing conditions

Single Reflow Profile
Double Reflow Profile
Single Reflow Profile+ 2h @ 150°C

TEST EQUIPMENT

The attachment strength of the BGA spheres to the substrate at different displacement speeds was measured using a Dage "4000HS" Bondtester (Figure 2)

Figure 2. Impact tester

This instrument has the capability of applying a displacement of 10 – 4000mm/sec in shear and 1 – 400mm/sec in tension. The configuration of the test is indicated schematically in Figure 3. The method of interpreting the plot of force as a function of the displacement of the solder sphere with respect to the test head is indicated in Figure 4. The work done in fracturing the sphere or detaching it from the substrate, the integral of force with respect to distance, is taken as the fracture energy.

$$\textbf{Fracture Energy} = \int F\,ds$$

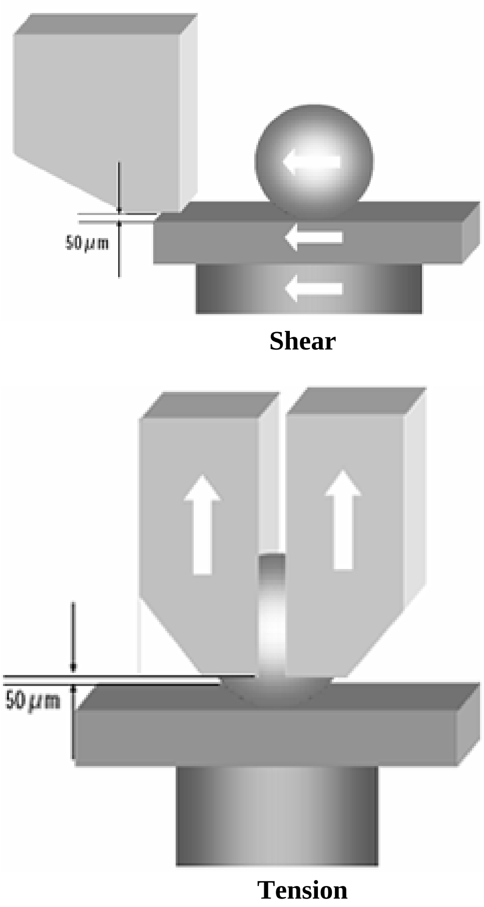


Figure 3. Schematic of test modes

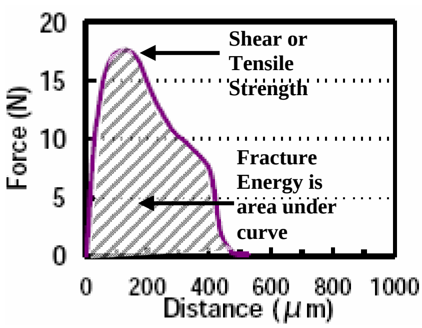


Figure 4. Typical test result.

Test pieces were sheared at speeds of 10, 100, 200, 1000, 2000 and 4000mm/sec and pulled at speeds of 1, 10, 100, 200, and 400mm/sec.

Although the results of testing at the highest shear and pull speeds are of interest from the qualitative point of view, confirming the trend towards increasingly brittle modes of fracture, limitations in the accuracy of the instrument at these high speeds diminishes the statistical significance of the measured forces and displacements. For that reason quantitative data is plotted only up to a shear speed of 2000mm/sec and a pull speed of 200mm/sec.

RESULTS

Three general types of failure modes were observed (Figure 5).

In type (a) failure fracture occurs through the body of the solder sphere and the fracture energy is high. The fracture surface indicates the solder has failed in a ductile manner.

In type (c) failure fracture occurs through the intermetallic layer and is brittle in character so that the energy required is small.

In type (b) failure fracture occurs partly through the intermetallic layer and partly through the body of the solder with mixed ductile and brittle character.

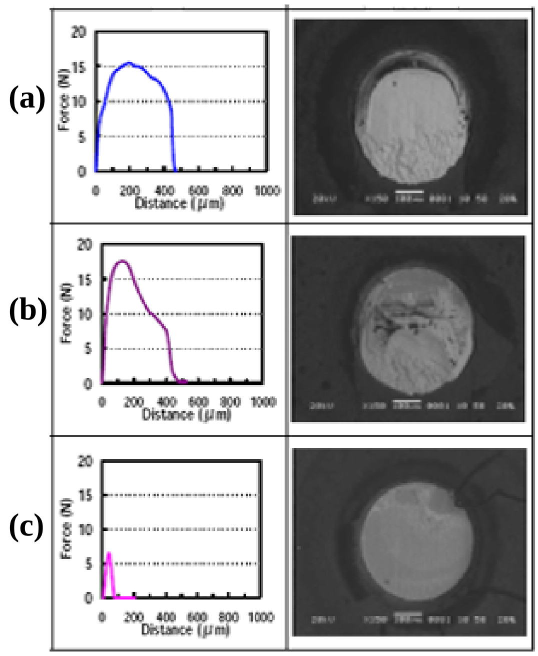


Figure 5. Failure modes in impact testing

An indication of the extent to which an impact fracture is ductile or brittle is provided by the amount of solder retained on the substrate surface. In Figure 6(a) failure has been ductile with the fracture surface being entirely solder. In Figure 6(b) the facture has been brittle with complete separation of the solder from the substrate at the interface

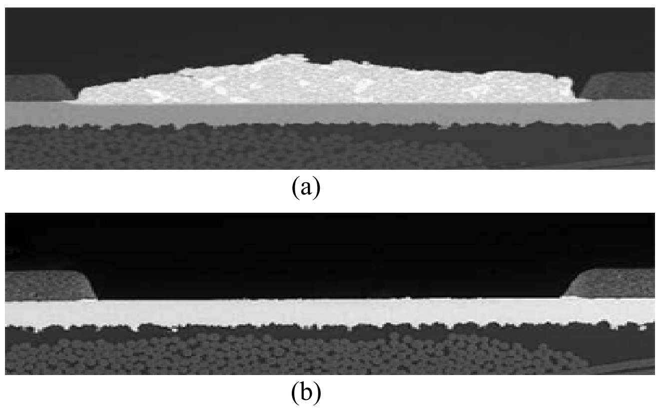


Figure 6. Solder retention in ductile (a) and brittle (b) failure modes

The character of the fracture surfaces of samples tested was quantified by estimating the percentage of the joint area covered by retained solder and examples of the appearance of the fracture surface with various percentages of solder is provided in Figure 7.

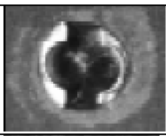
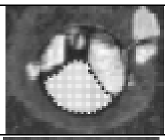
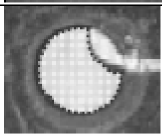
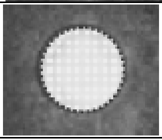
100%		70%	
30%		0%	

Figure 7. Method of quantifying the extent to which fracture is ductile.

The average fracture energy measured in testing in the shear mode is present in Figure 8.

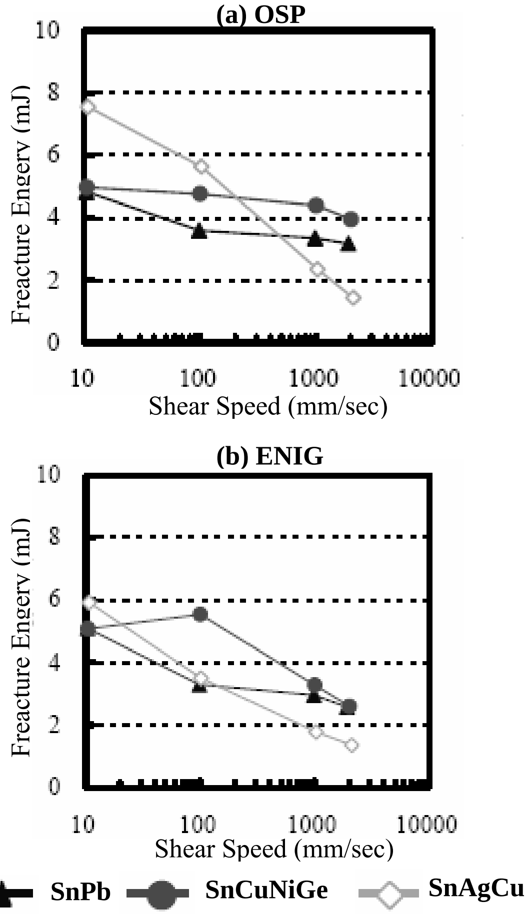


Figure 6. Average fracture energy as a function of shear speed

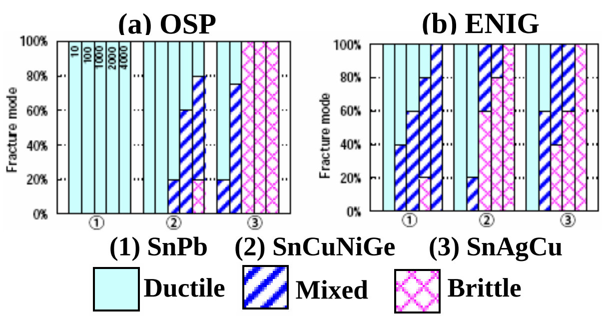


Figure 7. Fracture mode as a function of shear speed for each test piece

An indication of the trend of failure mode in shear testing is given in the summary of the fracture types for each of the five samples tested at each shear speed in Figure 7.

The percentages of solder in the fracture surface, indicating the extent to which the fracture mode is ductile, is plotted in Figure 8 for shear speeds up to 2000mm/sec.

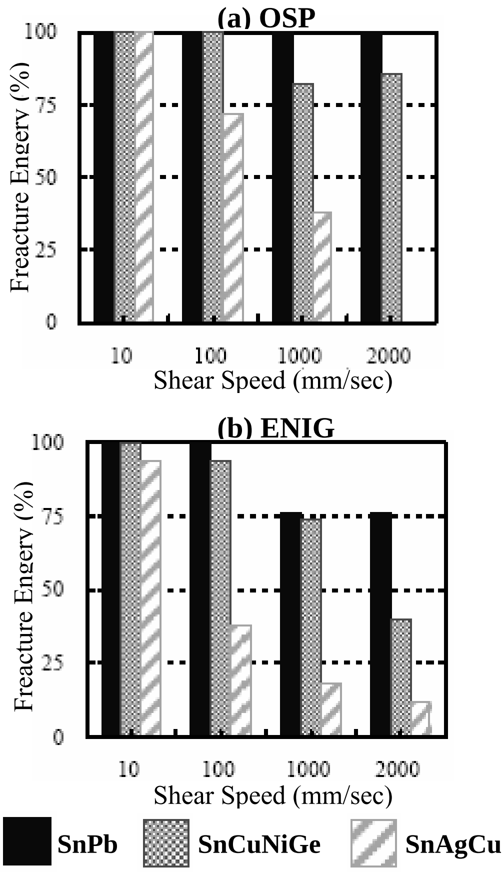


Figure 8. Proportion of Ductile Fracture

The measured fracture energy in the tensile mode is presented in Figures 9.

The character of the fracture surfaces of each of the five samples tested at each pull speed is summarised in Figure 10.

The percentages of solder in the fracture surface is plotted in Figure 11 for pull speeds of up to 200mm/sec.

The effect of ageing on the microstructure of the alloy/substrate combinations is presented in Figures 12, 13 and 14

The effect of ageing on strength and fracture energy as a function of finish at high and low rates of shear and pull is presented in Figures 15 and 16.

DISCUSSION

In shear testing of solders on a copper/OSP substrate (Figure 6(a)) the SnAgCu alloy has a higher fracture energy than either SnPb or SnCuNiGe at shear speeds up to 100mm/sec but at higher speeds the ranking is reversed. At 2000mm/sec the SnCuNiGe alloy has a fracture energy nearly four times greater than the SnAgCu and is a little higher than that of SnPb.

On the copper/ENIG substrate (Figure 6(b) the SnAgCu advantage largely disappears and fracture energy falls as the shear speed increases so that at 2000mm/sec it is about half that of the SnCuNiGe and SnPb.

The trend towards brittle fracture in the SnAgCu even at lower shear speeds and on both substrates is apparent in the higher incidence of mixed and brittle fracture modes (Figure 8).

The trends in pull testing are similar (Figures 9, 10, 11)

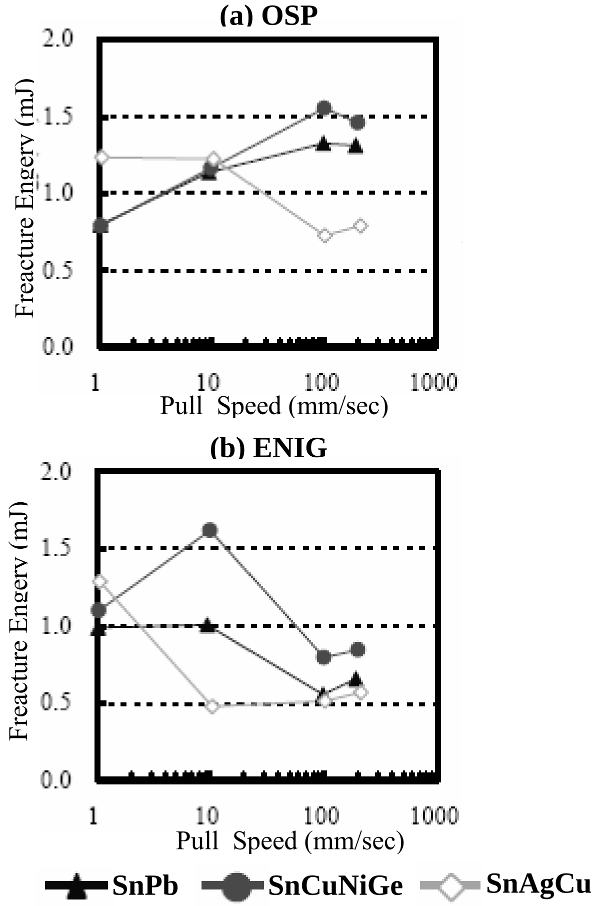


Figure 9. Fracture energy as a function of pull speed.

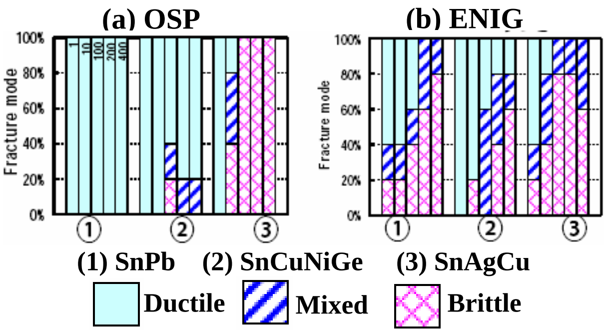


Figure 10. Fracture mode as a function of pull speed for each test piece

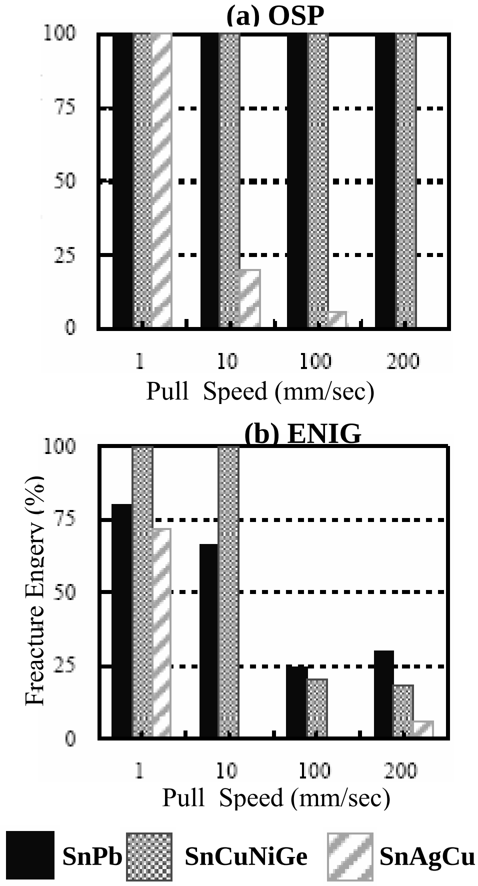


Figure 11. Proportion of Ductile Fracture

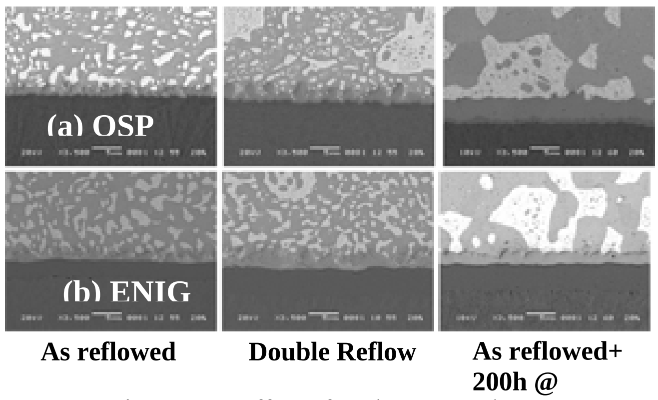


Figure 12. Effect of ageing on SnPb

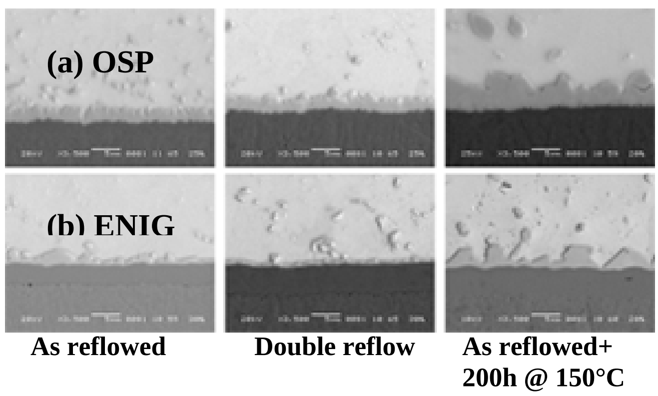


Figure 13. Effect of ageing on SnCuNiGe.

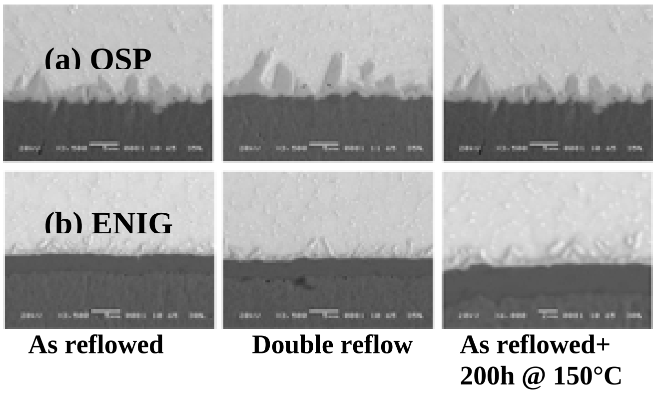


Figure 14. Effect of ageing on SnAgCu.

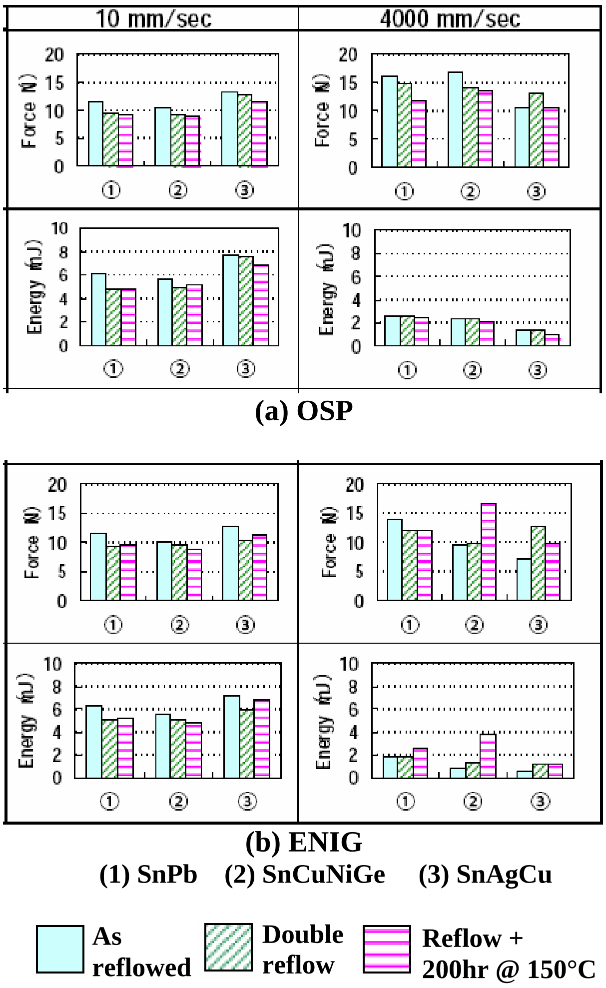


Figure 15. Effect of ageing on performance in shear

On ENIG (Figure 6(b) the fracture energy of the SnPb follows a similar trend to that on OSP. The failure strength of SnCuNiGe starts to fall away after 10mm/sec while that of SnAgCu starts to fall away after reaching a peak at 100mm/sec. The fracture energy of all alloys falls steadily to very low values with increasing shear rate.

Despite having a shear strength on ENIG comparable with that on OSP there is a significant proportion of brittle failure in the SnPb spheres at shear speeds greater than 10mm/sec. The proportion of ductile failure in the SnCuNiGe is higher than that of SnPb at 100 and 1000mm/sec at high speeds it is similar to the

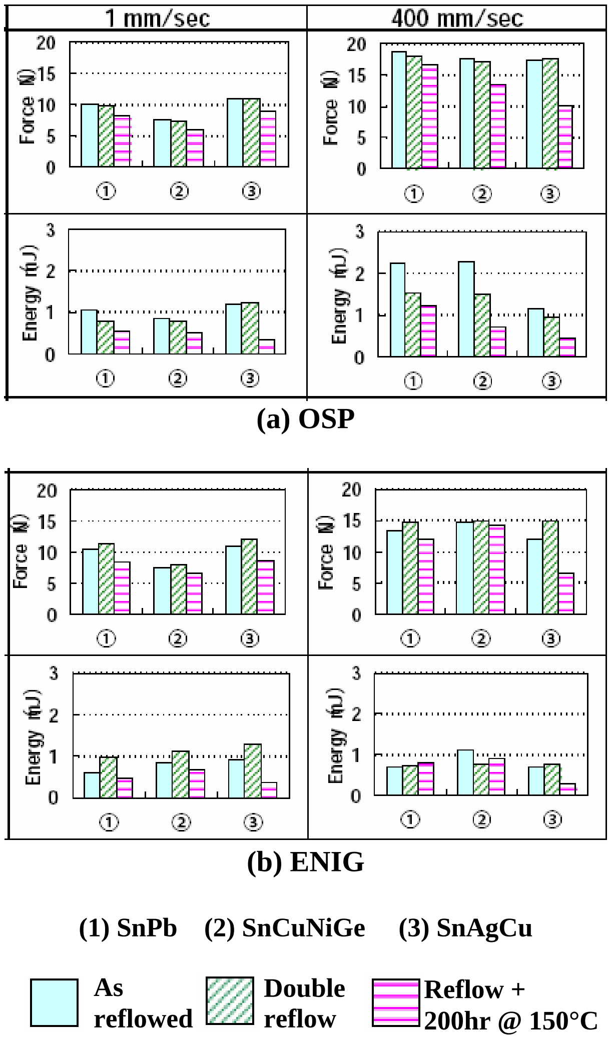


Figure 16. Effect of ageing on performance in pull test

SnAgCu with a high proportion of brittle failure in the fracture surface.

The additional thermal excursions reduced the strength and fracture energy in shear and tension of all alloys on OSP with the 200 hours at 150°C having the greatest negative effect (Figures 15(a) and 16(a)). An exception was SnAgCu on OSP tested at 4000mm/sec where the second reflow resulted in the greatest fracture energy but it is difficult to reconcile that with the thicker intermetallic apparent in the cross-section in Figure 14(a). The fact that a similar effect occurred in tension on OSP (Figure 15(a) suggests that indeed the second reflow has somehow increased the toughness of the joint.

On ENIG there is not a consistent trend of deterioration of strength and fracture energy with increasing thermal exposure. In fact the 200 hour ageing substantially increased strength and toughness of SnCuNiGe in shear at 4000mm/sec despite substantial increase in thickness and columnar character of the interfacial intermetallic (Figure 13(b)). There was a similar although smaller beneficial effect of the 200 hour ageing on the fracture energy of SnPb. In tension the trend of deterioration of strength and fracture energy is consistent across all alloys and pull speeds on an OSP substrate with the 200 hour ageing having the greatest negative effect. On ENIG, the strength of the SnCuNiGe joint seems unaffected by the second reflow or the 200 hour ageing while the strength and fracture energy of the SnAgCu alloy is substantially reduced even at a pull speed of only 1mm/sec.

ALLOY COMPARISON

In Figure 17 the average fracture energies in shear testing have been replotted on the basis that the fracture energy of SnCuNiGe at 10mm/sec is 100%.

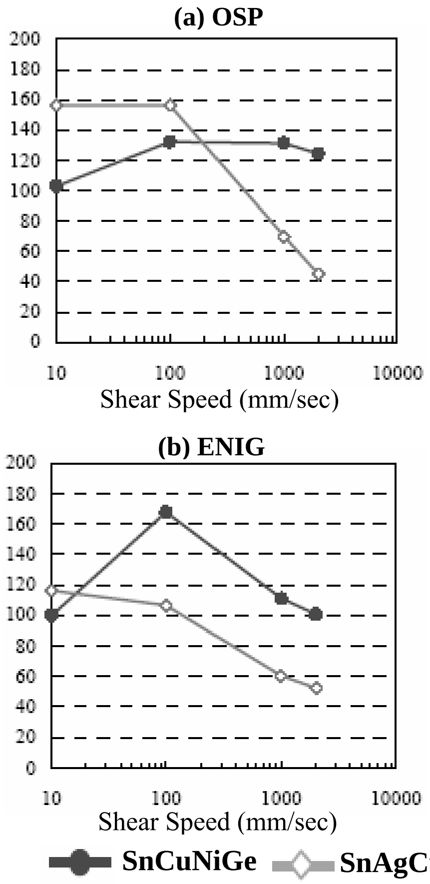


Figure 17. Variation in shear fracture energy from that of SnCuNiGe at 10mm/sec

On a copper/OSP substrate the measured fracture energy of the SnCuNiGe solder actually increases slightly with shear speed while that of SnAgCu falls off rapidly at speeds above 100mm/sec. On a copper/ENIG substrate the SnCuNiGe alloy maintains a substantial advantage in fracture energy at shear speeds above 10mm/sec.

In Figure 18 the average fracture energies in tensile testing have been replotted on a similar basis and the trends is similarly of higher fracture energy on OSP at pull speeds greater than 10mm/sec and on ENIG at all pull speeds greater than 1mm/sec.

Some insight into the microstructural features that contribute to the measured fracture energies is provided by cross-sections of the fractured test pieces (Figure 19 and 20)

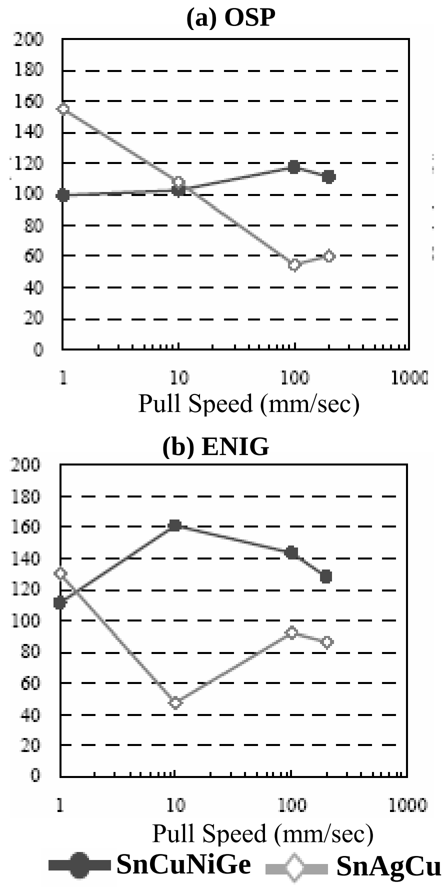


Figure 18. Variation from SnPb of pull test results on ENIG

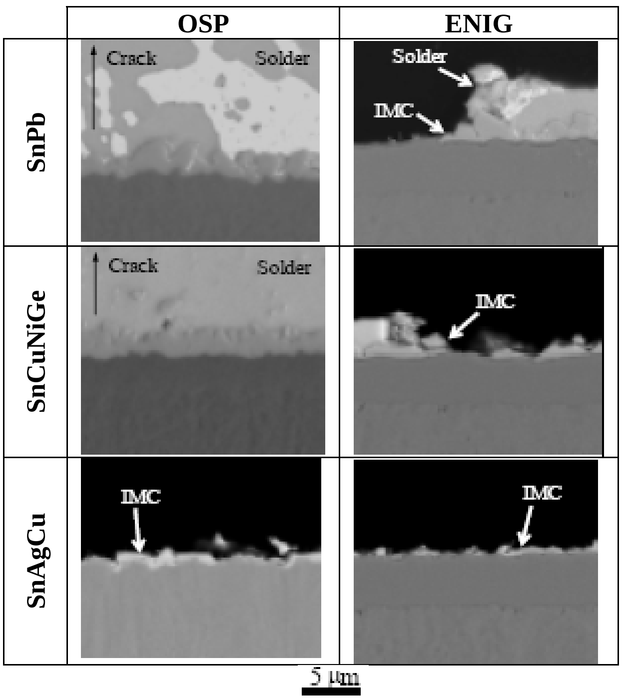


Figure 19. Cross-sections of Joints after shear testing

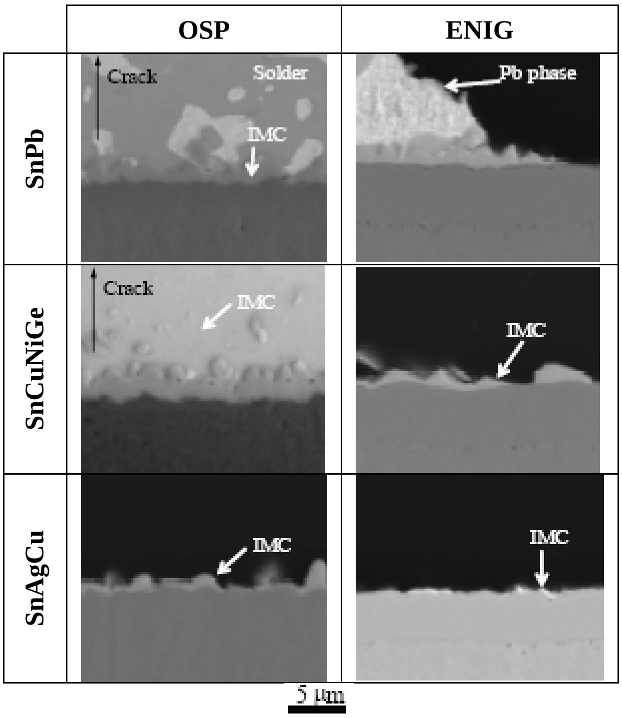


Figure 20. Cross-sections of joints after tensile testing

On the basis of these observations the inference can be made that the crack propagation pathways are as indicated schematically in Figure 21.

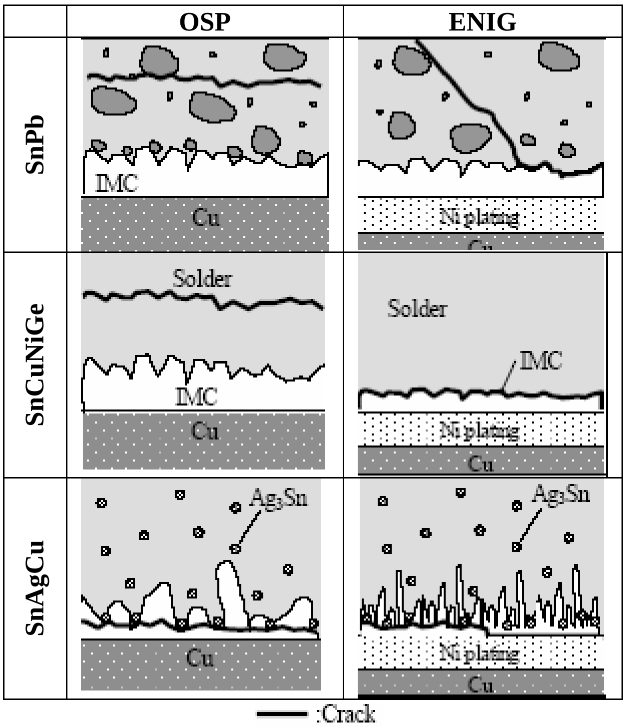


Figure 21. Typical crack pathways in impact loading

CONCLUSIONS

SnCuNiGe alloy spheres reflowed to OSP substrates retain a fracture energy comparable with that of SnPb at shear speeds of up to 4000mm/sec while at shear speeds greater than 100mm/sec the fracture energy of the SnAgCu is very low and in some circumstances close to zero.

On ENIG substrates the SnNi intermetallics seem to dominate behaviour in shear with all alloys failing in a brittle manner at high speed..

In pull testing the fracture energy of the SnAgCu at 400mm/sec is about half that of SnCuNiGe on both substrates.

Although generally having a negative effect on strength and fracture energy there is evidence that some sort of heat exposure can sometimes have a beneficial effect on fracture toughness. This is presumed to result from some changes in the nature of the interfacial intermetallic and this will be investigated further.

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