Analysis of BGA Solder Joint Reliability for Selected Solder Alloy and Surface Finish Configurations

Hugh Roberts / Atotech USA Inc
Sven Lamprecht and Christian Sebald / Atotech Deutschland GmbH
Mark Bachman, John Osenbach and Kishor Desai / LSI Corporation
Ron Huemoeller, YoonHa Jung and Robert Darveaux / Amkor Technology

Background

New challenges for the electronics industry are being incurred as a result of the global adoption of Pb-free initiatives. The microelectronics packaging sector is particularly impacted by these events as a result of changes to design, material requirements and assembly specifications. Solder alloys and surface finishes for package substrates (and PWBs) must meet the Pb-free requirements without resulting in reduced solder joint reliability. In addition, as a result of integration trends, circuit features and solder joints continue to shrink, further increasing reliability concerns. As a result, many material suppliers, fabricators, assemblers, contract manufacturers and OEMs are facing challenges to ensure the reliability of these packages. At the same time, these requirements must be met in a cost-effective manner to maintain competitiveness in the global electronics market.

The ball grid array (BGA) has been universally accepted as a reliable component packaging methodology, employing both wire bond and flip chip die-attach technologies. Figure 1 shows current and projected distribution of the IC packaging market and, in particular, illustrates the dramatic growth of the flip chip BGA segment.

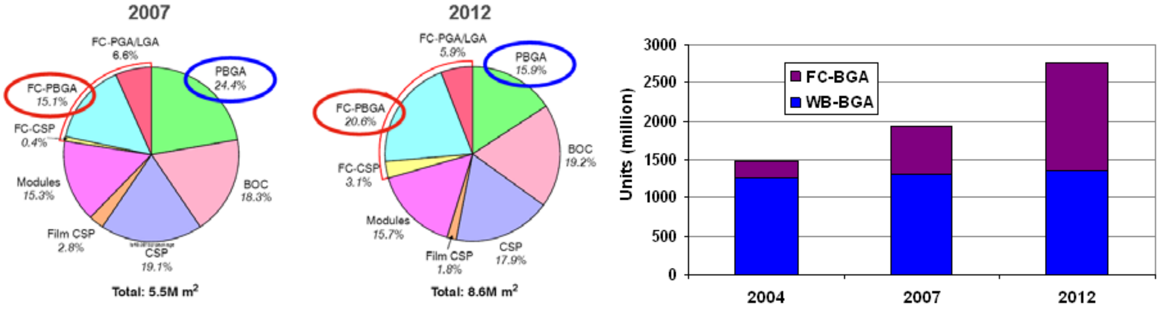


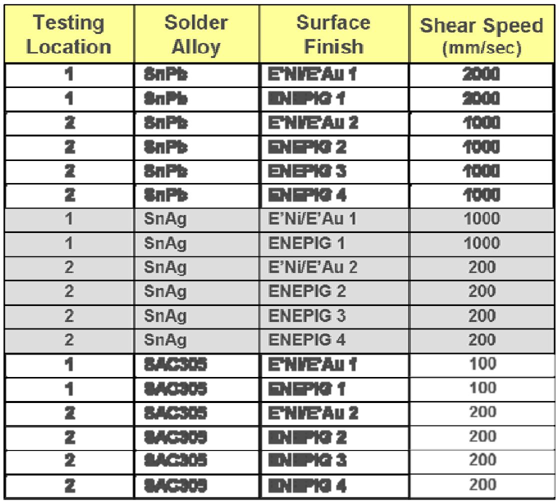
Fig. 1 Distribution of IC packaging market (left) and Projected growth of flip chip and wire bond BGA packages (Source: Prismark Partners)

This presentation summarizes the findings from part of a major ongoing project to evaluate the performance of several combinations of surface finishes and solder ball alloys for wire-bond and flip chip BGA package applications, while focusing on the flip chip segment of those investigations.

Solder Alloys, Surface Finishes and Test Vehicle

Based on results from an earlier screening phase, a surface finish of electroless nickel / electroless palladium / immersion gold (ENEPIG) was selected for in-depth evaluation in comparison to the process of record (POR), electrolytic nickel / electrolytic gold (E'Ni/E'Au). Both surface finishes were evaluated with solder balls comprised of eutectic SnPb (SnPb), Sn-2.3Ag (SnAg) and Sn-3.0Ag-0.5Cu (SAC305). Figure 2 shows the test matrix, including these combinations of solder alloys and surface finishes.

A special test vehicle was fabricated by the package substrate supplier, purposely designed to be more conducive to interfacial fractures between solder and pad finish or failure within the bulk solder (and less likely to produce pad lifting). The test vehicle was fabricated with approximately 6µm of non-patterned, plated copper on a flip chip substrate core, with an additional 25 µm of copper plated directly to achieve a minimum total copper deposit thickness of 30 µm. All pad openings were solder mask defined. Ball attachment to the test vehicles was performed at the package subcontractor assembly site to ensure more representative test samples. It is important to note that all devices were subjected to an additional Pb-free reflow cycle prior to high-speed ball shear testing. This action was taken to simulate PWB assembly (i.e. board attachment) and to establish the initial test time reference points. Figure 3 shows an example of the BGA test vehicle used for these high-speed ball shear investigations. Because of the nature of the test, solder balls were located only along two outer perimeter edges of the test vehicle, as shown in the figure.



Testing Location	Solder Alloy	Surface Finish	Shear Speed (mm/sec)
1	SnPb	E'Ni/E'Au 1	2000
1	SnPb	ENEPIG 1	2000
2	SnPb	E'Ni/E'Au 2	1000
2	SnPb	ENEPIG 2	1000
2	SnPb	ENEPIG 3	1000
2	SnPb	ENEPIG 4	1000
1	SnAg	E'Ni/E'Au 1	1000
1	SnAg	ENEPIG 1	1000
2	SnAg	E'Ni/E'Au 2	200
2	SnAg	ENEPIG 2	200
2	SnAg	ENEPIG 3	200
2	SnAg	ENEPIG 4	200
1	SAC305	E'Ni/E'Au 1	100
1	SAC305	ENEPIG 1	100
2	SAC305	E'Ni/E'Au 2	200
2	SAC305	ENEPIG 2	200
2	SAC305	ENEPIG 3	200
2	SAC305	ENEPIG 4	200

Fig. 2 High Speed Shear Test Matrix

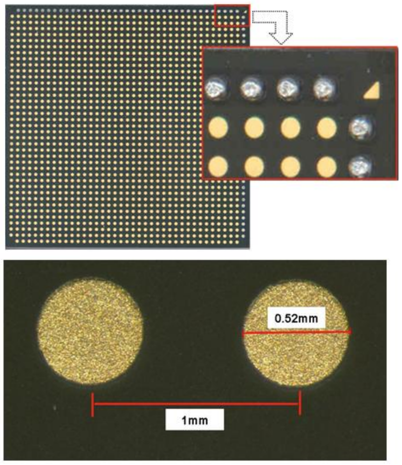


Fig. 3 High Speed Shear Test

Description of Testing

High-speed ball shear testing was used as the primary methodology for examining 2nd level solder joint reliability in this phase of the evaluation. Figure 4 shows the high-speed shear test equipment and an illustration of the test mechanism.

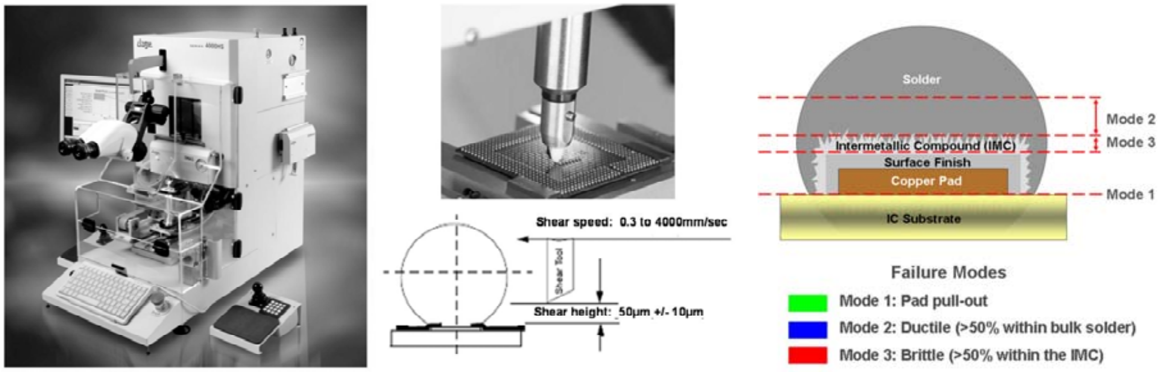


Fig. 4 Dage 4000HS High Speed Bond Tester (left) with detail of ball shear device (upper center) and illustration of ball shear mechanism (lower center) and failure mode description (left)

Determining the shear speed for each solder alloy involved use of a concept known as finding the "point of inflection" (POI), also known as the "transition point". This procedure involves a failure analysis screening that tests a sample at various shear speeds to determine a particular speed where the occurrence of brittle failures first appears in significant cases. The POI speed was determined for each of the three solder alloys on the POR finish (E'Ni/E'Au). Results of the high-speed ball shear testing include analysis of total energy, shear strength and failure mode. Total energy data provides additional information regarding the nature of the ball shear failure. Higher total energy readings typically relate to failures within the bulk solder, while lower energy results are indicative of brittle fractures along the bond interface. The evaluation included high-speed shear testing conducted within a period of 8 hours to 7 days after the Pb-free reflow (simulating board attachment), as well as after extended storage at high-temperature conditions.

Testing Results

High speed shear testing was performed at two different locations using identically fabricated samples. POI speeds were determined independently at both sites for each of the three solder alloys (refer to Figure 2). As shown in Figure 5, within one week of the Pb-free reflow (to simulate board attach) the SnPb solder performed more consistently in comparison to the SnAg or SAC305 alloys, although total energy results were somewhat lower. For the most part, the ENEPIG surface finishes provided results similar to the POR, although the ENEPIG surface finishes did achieve more consistent energy and shear strength results and a lower incidence of brittle failure with the SAC305 alloy. Although a high percentage of pad pull-out occurred for the SnAg and SAC305 alloys, it is still an indication that the bond interface was not the weakest point. Any effect of the different shear speeds used at the two testing locations appears to have been minimal.

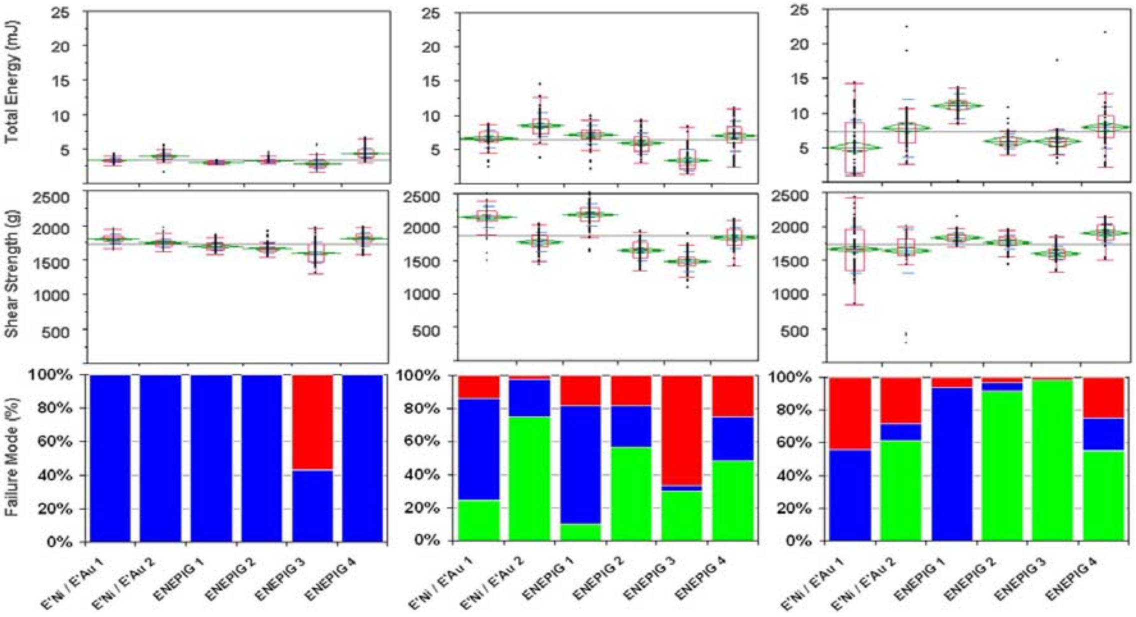


Fig. 5 Results of high-speed shear testing performed within 8 hours to 7 days after Pb-free reflow for SnPb solder alloy (left), SnAg solder alloy (center) and SAC305 solder alloy (right)

In comparison, Figure 6 shows high speed shear results for similar samples after extended high temperature storage. As shown, total energy levels have been reduced and a higher incidence of brittle fracture is evident for all alloys. The combination of SnPb solder with the POR surface finish achieved the highest percentage of ductile failure response. Overall, however, the performance of the ENEPIG surface finishes was again comparable to that of the POR for the SnAg and SAC305 alloy. The effect of the different shear speed may be evident with the SAC305 alloy, where measurably higher energy results are coupled with a high occurrence of ductile fracture for both the POR and ENEPIG tests performed at Location 1 and at lower shear speed (100 mm/sec).

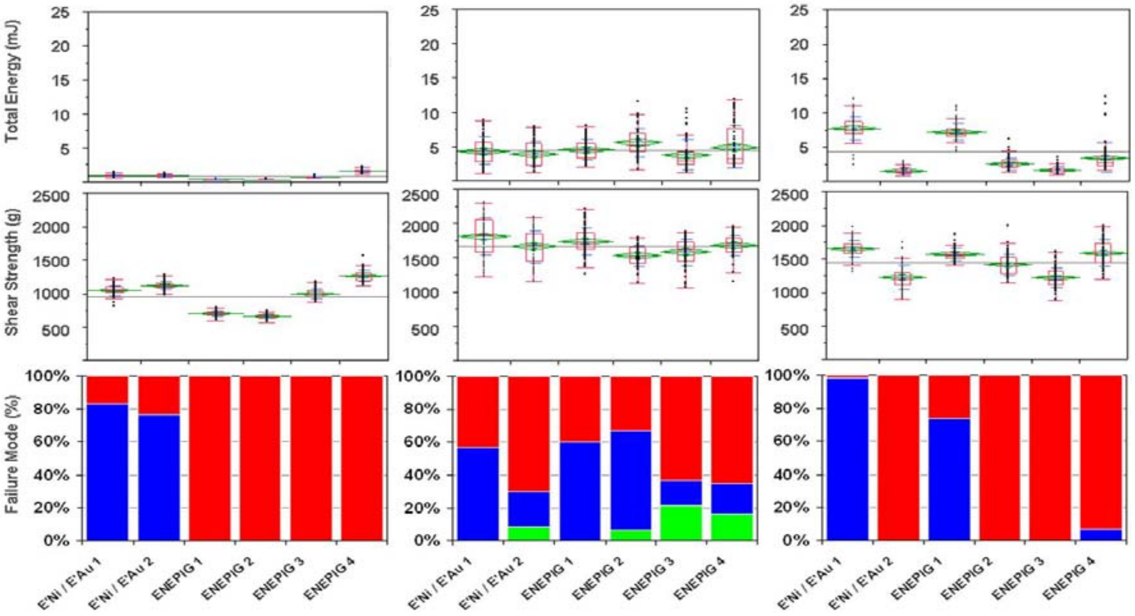


Fig. 6 Results of high-speed shear testing performed after storage for 1000hr at 150°C for SnPb solder alloy (left), SnAg solder alloy (center) and SAC305 solder alloy (right)

Figures 7 through 10 summarize the high-speed shear results for each test site at the different test conditions according to the type of surface finish. Figures 7 and 8 show results for the POR tested at Location 1 and 2, respectively. In both figures, the SnPb solder achieved a high degree of ductile failure response, but consistently produced very low total energy results in comparison to the other two alloys. Shear strength results were similar for all cases. In theory, any differences between the two figures should be attributed to the different shear speeds that were used. In Figure 7, the SAC305 alloy is shown to produce higher total energy results and a significant percentage of ductile fracture, even after high-temperature storage. By comparison, Figure 8 depicts very different results for the SAC305 after both high-temperature storage conditions. Furthermore, the SnAg and SAC305 alloys seem to indicate a better correlation between the total energy (and shear strength) results and the corresponding failure mode analysis.

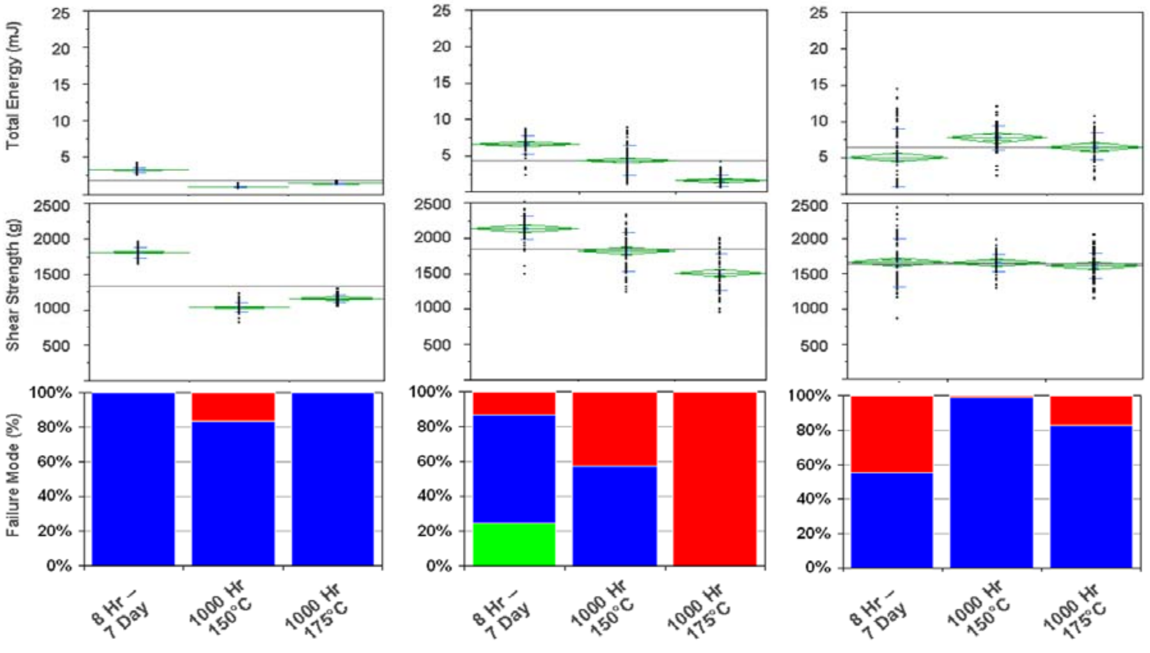


Fig. 7 High-speed shear test results performed at Test Site 1 for E'Ni/E'Au-1 surface finish at various test conditions for SnPb alloy (left), SnAg alloy (center) and SAC305 alloy (right)

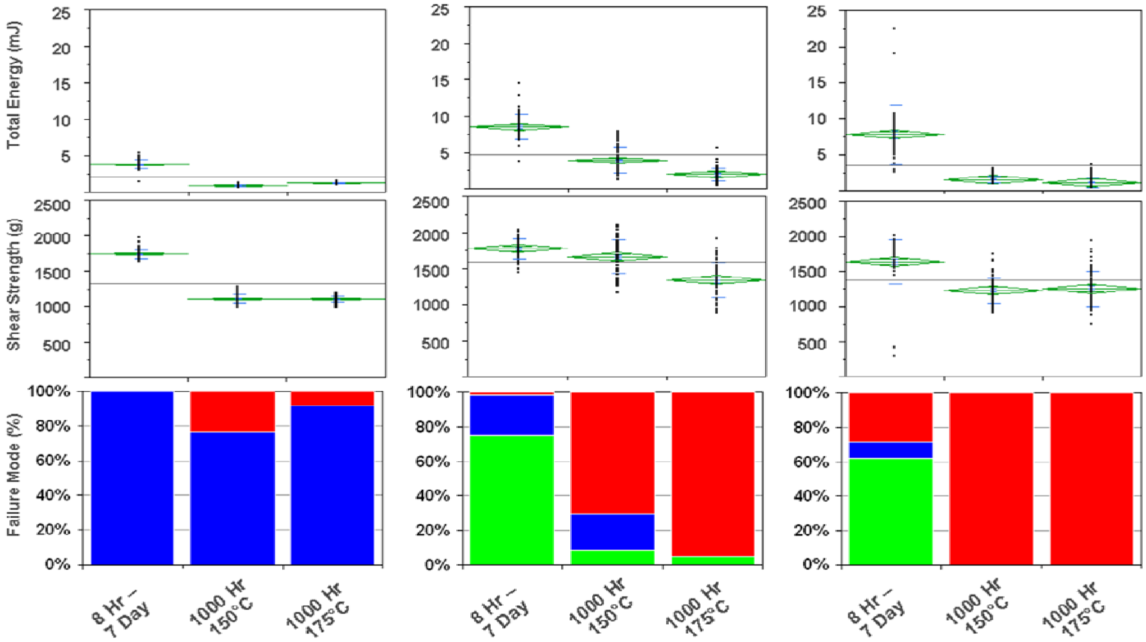


Fig. 8 High-speed shear test results performed at Test Site 2 for E'Ni/E'Au-2 surface finish at various test conditions for SnPb alloy (left), SnAg alloy (center) and SAC305 alloy (right)

Similar results are presented in Figures 9 and 10 for the ENEPIG finish tested at the two locations. In Figure 9, the results indicate that after high-temperature storage the SnAg and SAC305 performed better than SnPb when bonded to this surface finish. To some extent, this same trend is shown in Figure 10, although only with respect to the total energy and shear strength results. In comparing the two figures, for the SnPb and SnAg alloys there appears to be a high degree of correlation between results from the two testing sites. However, for the SAC305 alloy, the results in Figure 10 show considerably lower energy values, as well as a higher incidence of brittle failure mode, which again may be attributed to the higher shear speed.

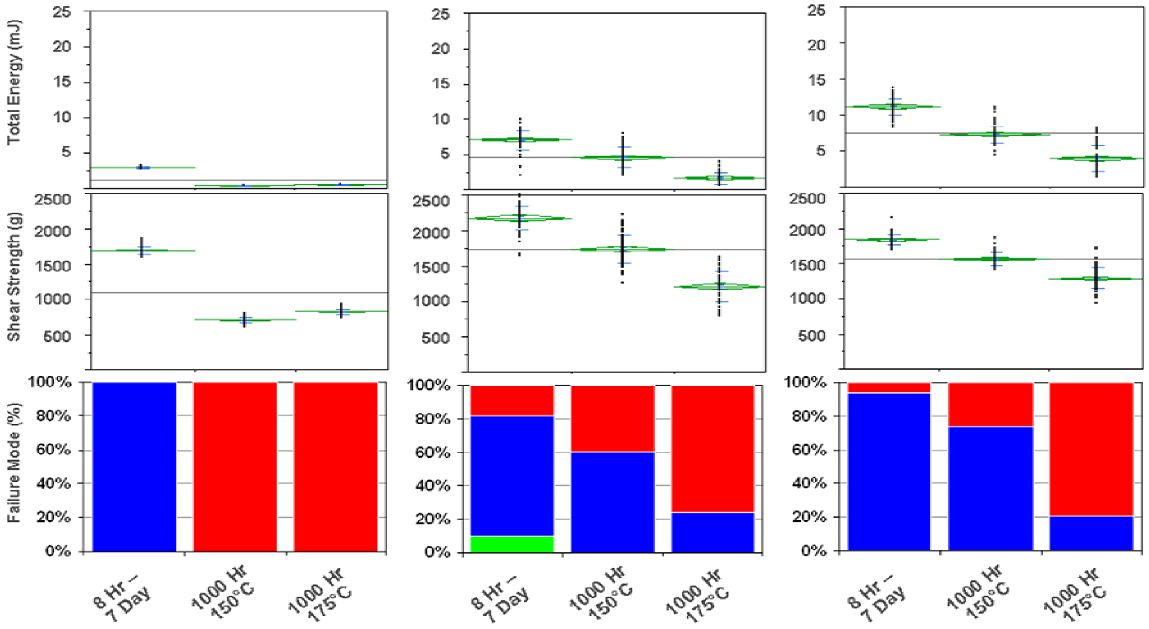


Fig. 9 High-speed shear test results performed at Test Site 1 for ENEPIG-1 surface finish at various test conditions for SnPb alloy (left), SnAg alloy (center) and SAC305 alloy (right)

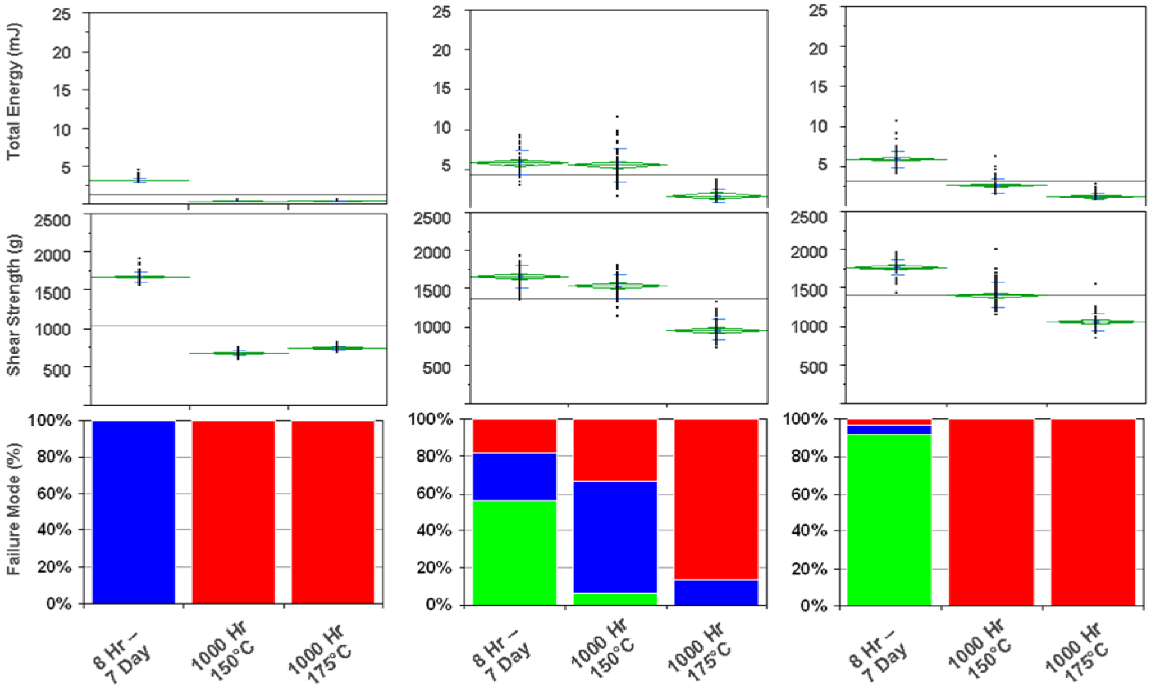


Fig. 10 High-speed shear test results performed at Test Site 2 for ENEPIG-2 surface finish at various test conditions for SnPb alloy (left), SnAg alloy (center) and SAC305 alloy (right)

Summary and Discussion

As previously noted, these results are part of an ongoing evaluation of surface finish and solder alloy combinations for both flip chip and wire bond BGA packaging. The results from this phase of the investigations can be summarized as follows:

1. Based on these and previous investigations, high-speed shear testing results appear to be very much dependent upon the shear speed selected. From these results, this effect of shear speed is primarily observed in testing performed after thermal aging. Also, the impact of testing at different shear speed appears to be more significant with the SAC305 alloy in comparison to the other two solders.
2. There appears to be a relatively good correlation between the failure mode, total energy and shear strength results. Because of the significant quantity of data, this statement is somewhat generalized, but for the most part, increases or decreases in all three parameters were typically observed.
3. A measurably better performance in terms of producing ductile failure mode was achieved with the combination of eutectic SnPb solder with the POR (E'Ni/E'Au), although in this case the other test results (total energy and shear strength) did not support this finding. Conversely, the effect of high-temperature storage was most dramatically demonstrated also by the SnPb alloy, but combined with the ENEPIG finish, where thermal aging had a significant negative impact for both test locations.
4. Overall, the performance of the solder alloys was similar for either the ENEPIG or POR surface finish. The SnAg alloy seemed to produce the most consistent results in terms of comparing both the two testing sites and the two different surface finishes, an interesting finding when considering the significant difference in the shear speeds used

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The presentation at the IMAPS 5th International Conference and Exhibition on Device Packaging will provide further details, discussion and interpretation of these test results.