Practical study to demonstrate an increase in the reliability of flip chip connections by adding nanoparticles to solder

David M. Harvey,
General Engineering Research Institute
Liverpool John Moores University
Liverpool, UK
d.m.harvey@ljmu.ac.uk

Teresa Partida Manzanera
University of Liverpool
Liverpool, UK
T.Partida-Manzanera@liverpool.ac.uk

Kangkana Baishya
Assam Engineering College
Guwahati, India
kbaishya010@gmail.com

Guangming Zhang
General Engineering Research Institute
Liverpool John Moores University
Liverpool., UK
g.zhang@ljmu.ac.uk

Mohd Arif Anuar Mohd Salleh Arif
UniMAP
Perlis, Malaysia
arifanuar@unimap.edu.my

Y. C. Chan
Liverpool John Moores University
Liverpool, UK
eeycchan@gmail.com

Nduka Ekere
Liverpool John Moores University
Liverpool., UK
n.n.ekere@ljmu.ac.uk

Derek Braden
Aptiv
Coventry, UK
derek.braden@apiv.com

Abstract— **The aims of the research are to improve the reliability and lifetimes of solder joints to contribute to the green economy, by reducing waste and extending recycling times. The objectives of the work are; to improve the materials properties of various solders used for attaching die/flip chip packages to PCBs by adding nanoparticles to the mix, to fabricate industrial test samples using flip chips soldered to PCBs, to test the reliability of the solder through accelerated testing, to examine failure modes and lifetime extensions.**

Keywords—nanoparticles in solder, solder joint reliability

I. INTRODUCTION

For over 50 years, SnPb solder has been used for electronic packaging due to its good solderability, good reliability and low cost[1][2][3][4]. However, lead/Pb is toxic for humans and harmful for the environment. The European Union's (EU) Restriction of Hazardous Substances (RoHS)[5] and Waste of Electrical and Electronic equipment (WEEE)[6] Directives mandated the elimination of SnPb solder from consumer electronics sold in EU market in 2006, and later from other products worldwide. Since then, Sn3.0Ag0.5Cu (SAC305) has become a popular lead-free solder alternative in the packaging industry for attaching electronic devices to printed circuit boards (PCBs)[7]. The main advantage of SAC305 is its lower melting point with respect most Pb-free solder alloys [8]. However, the high cost of Ag has driven the industry to look at less expensive alternatives such as low-silver alloys with Ag content <1.0 w% or Ag free alternatives such as SnCu-based solders[9]. Currently, SnCu solders with dopants such as Ni[10], Ge[11][12], Co[13] and Bi[14] or nanoparticles (NPs) such as Al2O3[15], TiO2[16], SiO2[17], or ZnO[18] to improve their performance, are the least expensive and most promising lead-free alternative[9]. Currently, there is a need to evaluate their reliability outside consumer applications, for example automotive applications where electronic components are often exposed to harsher environments[19]. This work will examine factors for improving solder reliability in the round, by considering electrical, mechanical and materials factors required, and which current research has made available for connections between components and circuit on a PCB.

Firstly a solder joint must satisfy the electrical connection required between circuits components. This must be reliable over a product's lifetime, and have the lowest possible electrical resistance. Secondly, the mechanical joint must be strong enough to keep all components attached during any conditions a product may face during its lifetime. Thirdly, the solder material must be designed to be solderable enabling easy manufacture of solder connections, and remain sufficiently stable to maintain the electrical and mechanical connection throughout a product's lifetime. With the thousands of solder joints in modern products it is worth reminding all users that if only one joint fails a product could fail, so reliability of every solder connection is imperative.

Research work conducted at LJMU and elsewhere during the last twenty years has found that not only the individual solder joints, but other factors can influence the reliability and degradation of electrical connection over time. It has been shown that in normal operation and in accelerated testing solder joints may crack and become open circuit rendering a circuit not fit for use. This can have catastrophic results such as plane crashes, car accidents and major disasters. It is fairly well known that materials sets and factors in the manufacturing such as choice of PCB surface finish, UBM on chip connections, as well as the solder chosen will influence reliability. It is less well known that the position of chips on a PCB will effect solder joint lifetimes, so PCB floorplan/layout and solder joint positions on a chip relative to the PCB edges can accelerate failure. Double-sided PCBs are interesting as failure modes based on chip position on a PCB can be different for thermal cycling and vibration tests. This makes the optimum choices for each chip's position difficult and application dependent, to be considered by the circuit designers and reliability engineers.

There now follows a short review of the research into the addition of nanoparticles into lead-free solder, some highlights demonstrating their value to the integrity of the solder joint, practical test results from the team, future research work to refine the solder design, manufacture and test, and brief conclusions.

II. SHORT REVIEW OF NANOPARTICLE RESEARCH FOR SOLDER JOINTS

New solders have been developed by the academic partners using a variety of nanoparticles (NPs) introduced into various base solders. These include SAC 305, Sn0.7Cu and low temperature solders such as Sn58Bi. Solder balls were manufactured to connect industrial grade flip chips to FR4 PCBs with devices having 109 and 12 balls. Once connections made the reliability of interconnection was testing through thermal cycling and through vibration. Aggressive test profiles were used to accelerated the tests and suitable for application in the automotive sector. Solder joints were scanned using ultrasound for cracks at appropriate intervals as the test progressed to non-destructively monitor progression of any failures from manufacture to end-of-life.

Previous work has introduced nanoparticles of silver or tungsten to Sn58Bi and will be briefly reported here.

Sn58Bi is a contender when low temperature soldering is required for use where low temperature packaging, heat sensitive devices and low CTE mismatch is necessary. Studies have been concluded to show that by the addition of nanoparticles to Sn58Bi solder the mechanical strength can be enhanced [28]. For 1% weight of silver/Ag nanoparticles added to Sn58Bi it can be seen that the nanostructure in Figure 1 for 76nm Ag particles is more refined than for the standard solder and for 31nm or 133nm Ag particles, and has the best mechanical properties.

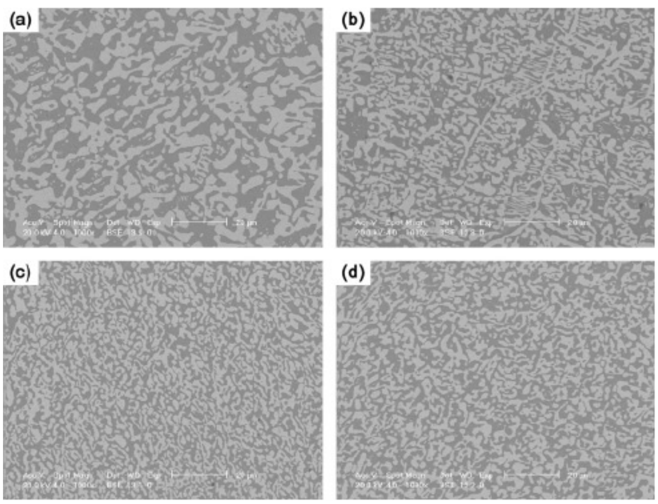

Fig.1. Microstructures of solders: (a) Sn58Bi, (b) 31 nm Ag particle doped, (c) 76 nm Ag particle doped and (d) 133 nm Ag particle doped. [20]

Fig. 1 illustrates how nanoparticles can refine microstructure in Sn58Bi solder when an optimum nanoparticle size found, and Fig. 2 how silver nanoparticles have increased micro hardness and shear strength in Sn58Bi solder [20].

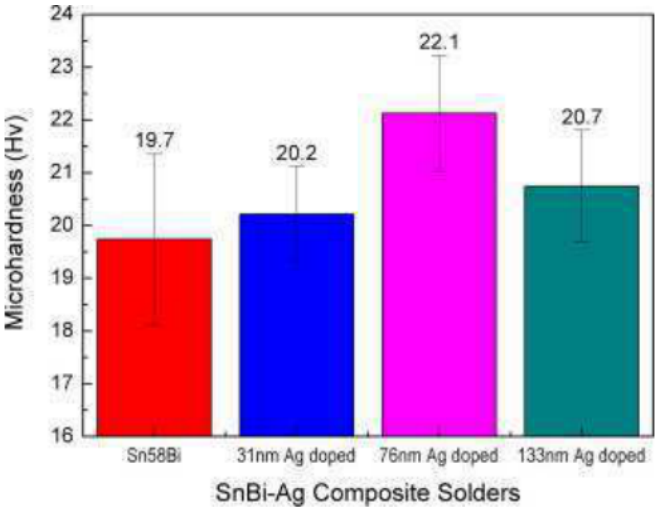

Fig. 2. Vickers microhardness of Ag-free and Ag-containing composite solders.[20]

Another interesting study illustrated that the addition of 1% weight of Tungsten/W to Sn57.6Bi0.4Ag improved the properties [22] Fig. 3. The improved micro structure contributes to enhanced physical properties. The microhardness increased by 6.2% and the shear strength of the solder was enhanced by 8.2%.

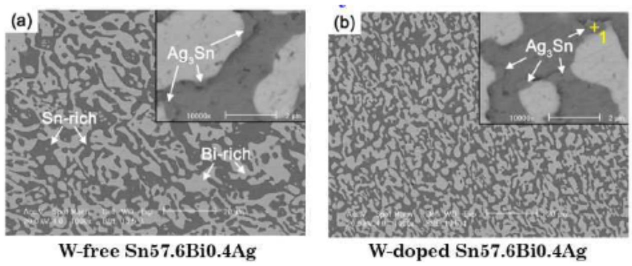

Fig. 3. Microstructure of (a) Sn57.6Bi0.4Ag solder and (b) Sn57.6Bi0.4Ag-W nanocomposite solder. [22]

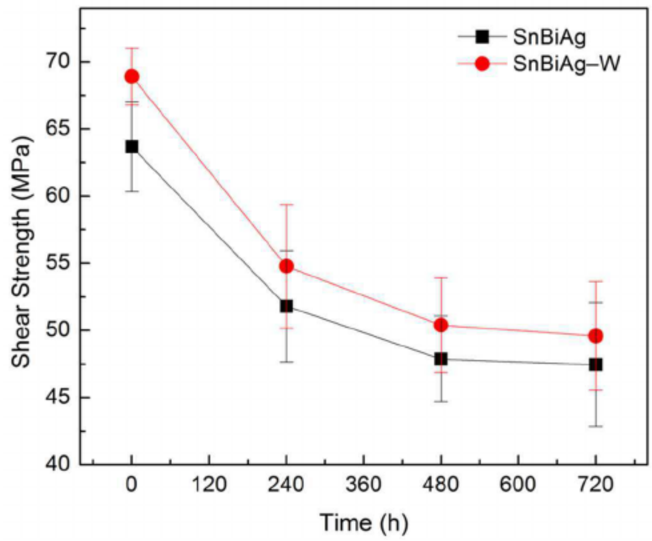

Fig. 4. Shear strength v aging time for SnBiAg and SnBiAg with W nanoparticles solder balls [22]

Fig. 4 shows for 720 hours aging at 100 degrees C shear strength performance was improved throughout the test by the addition of W nanoparticles.

In an attempt to create a greener solder the popular SAC305 solder alloy was reinforced with kaolin geopolymer ceramic particles [24]. The particles were at the micro scale rather than nano scale but the results were significant. SAC305 solder powder with mean particle size of 31.557 microns was mixed with small amounts of kaolin geopolymer ceramic powder with a mean particle size of 18.41 microns. Various weight percentage (wt.%) of kaolin geopolymer ceramics (0, 0.5, 1.0, 1.5 and 2.0 wt.%) were used to form the solder samples.

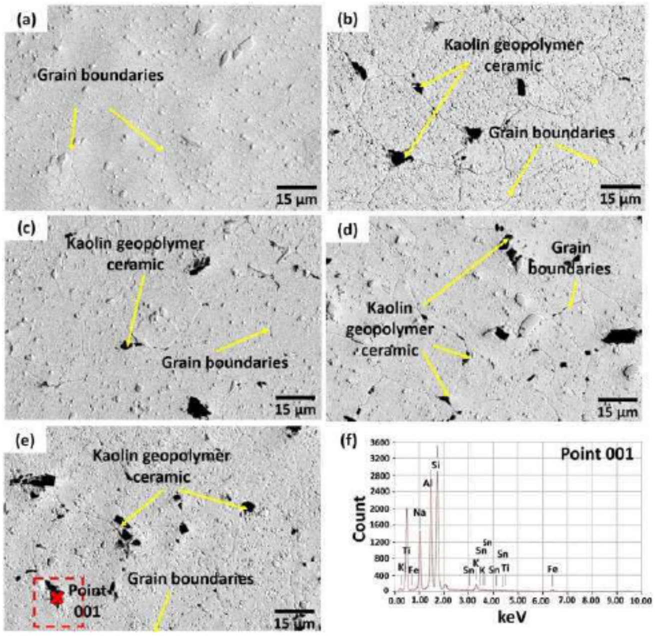

Fig. 5. SEM micrograph of sintered SAC305/kaolin geopolymer ceramic samples showing distribution of kaolin geopolymer ceramic at (a) 0 wt.% kaolin geopolymer ceramic, (b) 0.5 wt.% kaolin geopolymer ceramic, (c) 1.0 wt.% kaolin geopolymer ceramic, (d) 1.5 wt.% kaolin geopolymer ceramic, (e) 2.0 wt.% kaolin geopolymer ceramic and (f) EDX point analysis at Point 001.

The average shear strength of kaolin geopolymer ceramic enhanced SAC305 is given in Fig. 6 (a). All additions of the geopolymer from 0.5 weight % to 2 weight % enhanced the strength with a peak of 13.01 MPa when 1% weight of geopolymer added. Fig. 6 shows surface features for all the solders tested after fracture. More dimples were observed in the samples containing kaolin geopolymer ceramic which correlates with better plastic properties for ductile materials. However, as the addition of kaolin geopolymer ceramic beyond 1.0 wt.%, large dimples were observed at the fracture surface which may explain the drop in the shear strength of the samples at 1.5 wt.% and 2.0 wt.% .

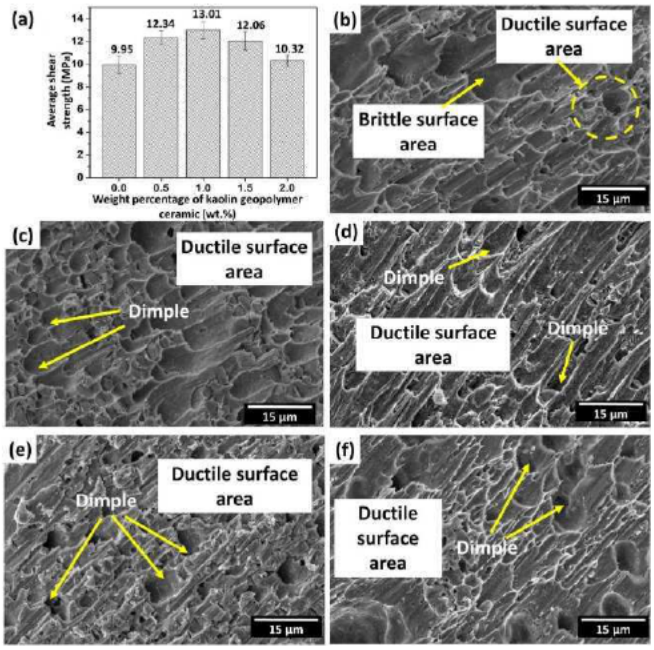

Fig. 6. (a) Average shear strength of SAC305 lead free solder with different wt.% kaolin geopolymer ceramic, SEM micrograph of fracture surfaces of pure SAC305 and kaolin geopolymer ceramic reinforced SAC305 composite solders at different weight percentage of kaolin geopolymer ceramic; (b) 0 wt. % kaolin geopolymer ceramic, (c) 0.5 wt.% kaolin geopolymer ceramic, (d) 1.0 wt.% kaolin geopolymer ceramic, (e) 1.5 wt.% kaolin geopolymer ceramic and (f) 2.0 wt.% kaolin geopolymer ceramic.

III. PRACTICAL RESULTS DEMONSTRATING VALUE OF NANOPARTICLES TO IMPROVE SOLDER MECHANICS

A recent review of lead-free solders that have incorporated micro or nano particles was completed in 2020/2021 [21]. Work to date has demonstrated the potential to improve some properties of solder joints by:

1. Incorporation of a small percentage of nanoparticles to a solder material. Typically up to 1% by weight, but smaller fractions have been reported with positive results.
2. Addition of a very small percentage of nanoparticles has a negligible influence on the melting points of each solder alloy.
3. The formation and growth during a solder joints lifetime of inter-metallic compounds (IMCs) is limited by suitable nanoparticles.
4. Optimum size of nanoparticles has to be found for each additive, as particle agglomeration and adsorption need to be considered for each case.
5. Mechanical strength of solder can be increased, reported at up to 18.9% [20].
6. Solder with nanoparticles fatigue life extended by up to 41.9% [21, 25]
7. Electrical conductivity will be changed but only marginally.
8. Electro-migration is hampered by the new structures that contain nanoparticles, increasing reliability
9. Thermo-migration is also reduced, improving longevity.

IV. ONGOING RESEARCH WORK

This leads to research to evaluate the impact of the addition of the geopolymer ceramic NPs on the reliability of Sn0.7Cu solder. For this two custom designed flip-chip packages were fabricated using Sn0.7Cu and Sn0.7Cu+nanoparticle solder joints, respectively. Test fixtures were made with 9 silicon flip-chips with area ~9 x 4 mm and thickness 525 µm mounted on a ~ 10 cm x 10 cm area and 1.6 mm thick FR4 PCB, using twelve 600 µm diameter solder balls to solder each chip onto the PCB. Accelerated thermal cycling (ATC) tests were set according to the JEDEC standard 22-A104D test condition B with a maximum temperature of 125 °C, a minimum temperature of - 55 °C, and a dwell time of 15 min at each temperature. The total cycle time was 71 min, with average ramp up rate of 9.7 °C/min and ramp down rate of 8.8 °C/min. At this time reliability has proved to be 100% as after 500 hours of thermal cycling no errors have occurred. Further reliability results will be presented as soon as any failures occur.

V. CONCLUSIONS

The addition of nanoparticles to solder definitely has benefits. By the addition of < 1% weight of a suitable nanoparticle many physical and engineering properties can be enhanced. Although research work is still expanding and solder mixtures are constantly being developed to meet various applications, so far no perfect solution has been disseminated or knowingly taken up by manufacturing industries. It is amazing that such a small percentage of added nanoparticles can increase the mechanical strength on solder bonds, slow down degrading of IMC layers and slow electromigration and thermo-migration. The joint working between materials scientists and engineers will continue to increase our understanding of how and why solder joints fail and how we can extend solder joint lifetimes, improve reliability and hence make electronics greener as less failure means less recycling.

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