Advanced Microsystems Assembly using Screen Printing Technology

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1. Introduction

This article presents the results of an EPSRC-funded project (Microsystems Assembly Technology for the 21st Century, MAT21) carried out by two British Universities (Greenwich and Heriot Watt) and a host of industrial partners (Celestica, DEK, Cookson-SPM, Merlin, Hewlett Packard and Micro-Emissive-Displays) covering the full electronic packaging supply chain. This multi-disciplinary project seeks to produce a low cost, high volume, low temperature (T<100°C) environmentally friendly assembly technology using micro-engineered interconnections at sub-100μm pitch.

The continuous strive towards smaller, lighter, and smarter products have driven the need for advanced packaging techniques such as flip-chip assembly [1]. The advantages of flip-chip bonding in mainstream microelectronics are well documented [1,2]; of particular interest for MicroSystems Technology (MST) Packaging is the requirement of a low temperature bonding process.

In the MAT21 project, interconnections are achieved by electroforming copper columns that are bonded onto advanced organic substrates [3]. Isotropic Conductive Adhesives (ICAs) are to be bonded onto advanced organic substrates [4] using stencil printing. The primary aim of the project was therefore to develop a process to produce successful and consistent quality deposits using screen printing at sub-100μm pitch. To achieve this, stencils were developed and fabricated at the MicroSystems Engineering Centre (MISEC), Heriot-Watt University, using advanced microengineering techniques. Computational simulations of the printing process (from a fluid mechanics and rheological points of view) and behaviour of the stencils were carried out by the Department of Computing and Mathematical Sciences, University of Greenwich in conjunction with the rheological experiments and characterization studies of the various materials implemented at the School of Engineering, University of Greenwich. Moreover current

and developed models were used to predict the reliability of such microsystem assembly processes with the underfill characteristics and to identify process weaknesses. All phases of the project are presented.

2. Enhanced solder paste stencils for sub-100μm pitch deposits.

The purpose of a stencil is to allow the transfer of solder paste, conductive adhesive or other similar material through its apertures onto a given substrate. Screen printing through a metal foil is an effective, fast and low cost process for chip and wafer bumping. As the push towards large interconnection density drives down stencil aperture pitch below 100 microns, metal stencil manufacturing techniques based on current wet etching or laser cutting technologies become unsuitable. Small aperture stencils cannot be produced reliably using chemical etching, primarily due to the undercutting process of the etching step. Laser cut is a sequential process; as the number of apertures increases so does the time and cost of producing each stencil. Moreover the difficulty of controlling the interaction between the laser beam and the metal foil cannot guarantee systematic smooth aperture sidewalls that prevent the retention of the paste during printing. Although conventional electroforming techniques can generate stencils with such aperture size, good reproducibility of the aperture shapes at such low pitch cannot be guaranteed.

The stencil, shown in figure 1, stems from a patented process currently being spun-out through the company MicroStencil [4]. Perfectly vertical sidewalls are produced with apertures closely following the resist sidewalls during the electroforming process. The electroforming process generates the desired mechanical properties of the metal across the whole stencil. Custom built equipment used to fabricate the stencil includes a doctor blade machine for the spreading of the thick photoresist (used as a mold in the electroforming process) and a highly collimated UV-light exposure gun for photo-patterning. Knife coating the photoresist through the doctor blade spreader has been shown to generate better thick photoresist (good planarity, absence of beading effects and ripples) layers than by spin coating. Apertures ranging from 1000μm to 20μm were successfully demonstrated on a 50μm nickel foil as shown in figure 1.

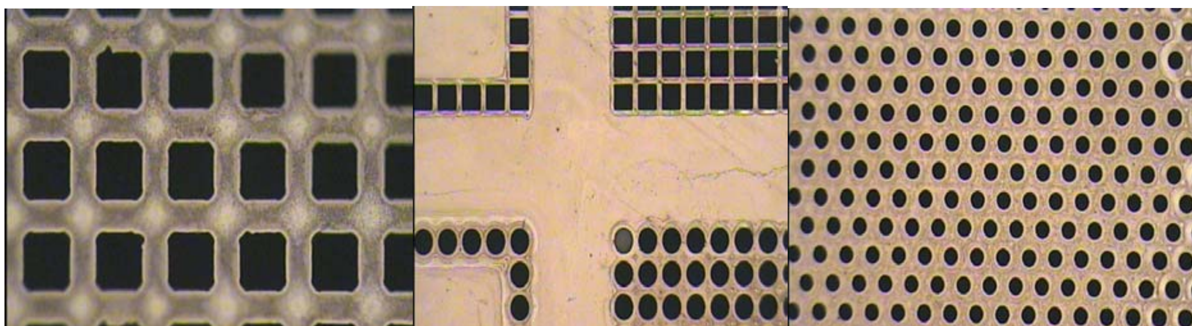

Figure1, from left to right: 20μm diameter square apertures, 30μm pitch; 50μm apertures, 70μm pitch; 50μm diameter circles at 90μm pitch.

3. Rheological characterisation of the pastes and adhesives.

Rheology is the science of flow and deformation of matter when subjected to stress. The rheology/flow behaviour can be correlated to the performance of the materials during the stencil printing process. A Reologica StressTech controlled stress and strain rheometer was used to investigate ICAs rheological properties and to compare them with conventional solder paste. A sample thickness of 0.5mm is sandwiched between two smooth flat plates having a 40mm diameter, figure 2. The deformation of the sample can be measured in either a controlled stress or controlled strain mode.

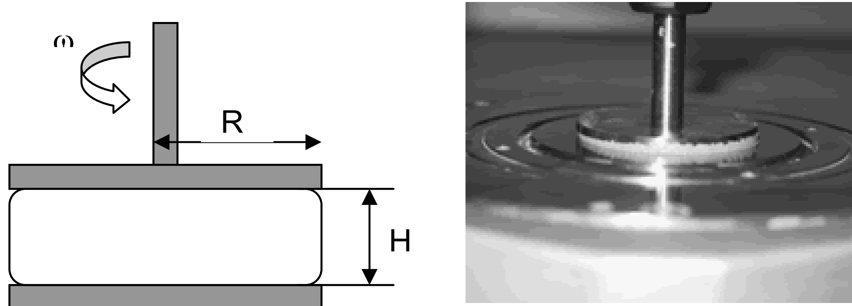

Figure 2, Stress and strain rheometer test

ICAs are also used for bonding electronics devices mainly for low temperature applications. The ICAs studied in this project consist of 70-80% metal fillers dispersed in an epoxy resin. During curing, the epoxy resin shrinks, enabling the contact of the metal fillers and hence the conduction of electricity. Due to the low temperature (-40˚C) storage requirements of the adhesive, gentle stirring of the samples in their original jars for approximately 30 seconds before loading onto the rheometer is a necessary preparatory procedure. Once loaded, no pre-shear was applied. The samples are deposited onto the bottom plate of the rheometer. The top plate was then lowered to the desired gap (0.5mm), squeezing the extra paste out from between the plates. Excess paste was trimmed from the edges of the plates to minimise edge effects.

Steady shear rheometry involves the measurement of viscosity at different shear conditions. The sensitivity of a sample to changing shear rates is evaluated (shear thinning, thixotropy, hysteresis, etc). Shear thinning properties (the reduction of viscosity of a material when sheared) are essential to assist the entry of paste into the stencil apertures. The experiment was conducted at 25°C and the relative humidity was monitored. During the printing process, solder paste experiences a range of shear rates in the range of 0.01 to 1000/s and more [5]. Although the shear rates investigated here are low, they can be used to predict the flow properties during stencil aperture filling and paste release.

In Figure 3, the viscosity as a function of shear rates is shown for types of solders pastes (X2 & T3) and conductive adhesive samples (P1). The sample T3 shows the highest viscosity followed by X2 and P1. A further analysis of the experimental data was carried out using the Cross Model [6] shown in equation 1, where η is the viscosity, η_∞ is the viscosity at infinite shear rate, η_0 is the viscosity at zero shear rate, K is associated with the breaking of structural linkages and m is a dimensionless constant. The degree of shear thinning is dictated by the value m: m tending towards unity represents shear thinning liquid while m tending towards zero represents Newtonian liquids.

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = \frac{1}{1 + K\dot{\gamma}^m} \quad \text{(equation 1)}$$

From equation 1, η_0 and η_∞ are estimated, including *K*, *m* and correlation coefficient, *r* as shown in table 1.

From the table 1, the viscosity measured for the solder paste samples (X2 and T3) is higher than that of the isotropic conductive adhesives (P1). Based on the constant m, sample P1 and X2 showed a higher degree of shear thinning compared to sample T3. Between the samples X2 and T3, zero shear viscosity of T3 was much higher compared to X2. From the zero shear viscosity values, sample T3 showed a much higher resistance to flow compared to the two other samples. But the infinite shear viscosity of P1 and T3 are low compared to that of X2. The drop in viscosity is a good indication of structural re-arrangement of the particles in the direction of flow, which promotes the aperture filling during the stencil printing process. All samples showed a good fit to the Cross model.

Model Parameters	P1	X2	T3
η_0 *(Pa s)*	6025	27640	33060
η_∞ *(Pa s)*	45	62	79
K (s)	21	62	26
m	0.85	0.98	0.97
r	0.98	0.99	0.90

Table 1, Rheological constants defined by the Cross model for solder paste (X2, T3) and ICA (P1)

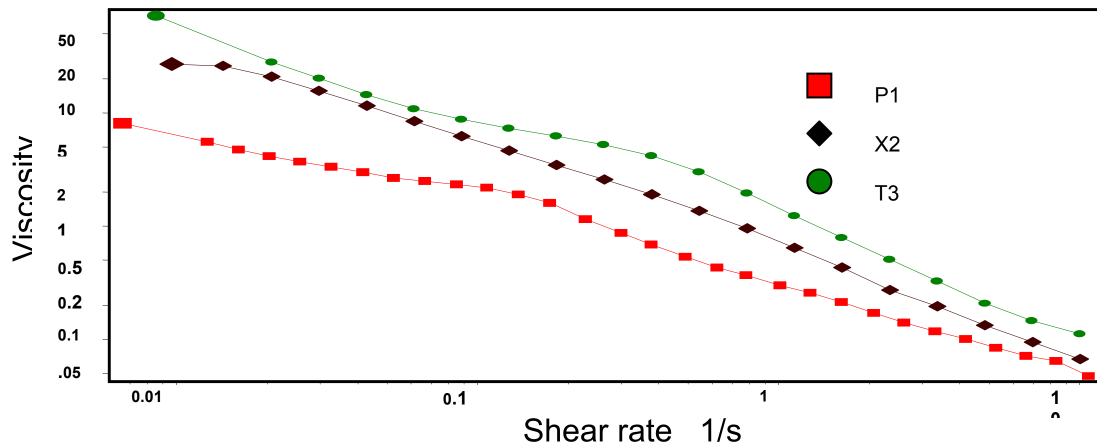

Figure 3, Variation of solder paste and ICAs viscosity measured at different shear rate

4.0 Modelling Results

Computational Fluid Dynamics (CFD) have been used to simulate the macroscopic bulk motion of adhesive paste ahead of a moving squeegee blade during the stencil printing process. Figure 4 details the geometry to be simulated and results of velocity vectors across a stencil. The computational mechanics code – PHYSICA [8] – was used for these simulations. Non Newtonian fluid dynamics is simulated by solving the Navier Stokes equations for flow with the Cross Model constitutive law, as detailed above, to characterise paste rheology [9]

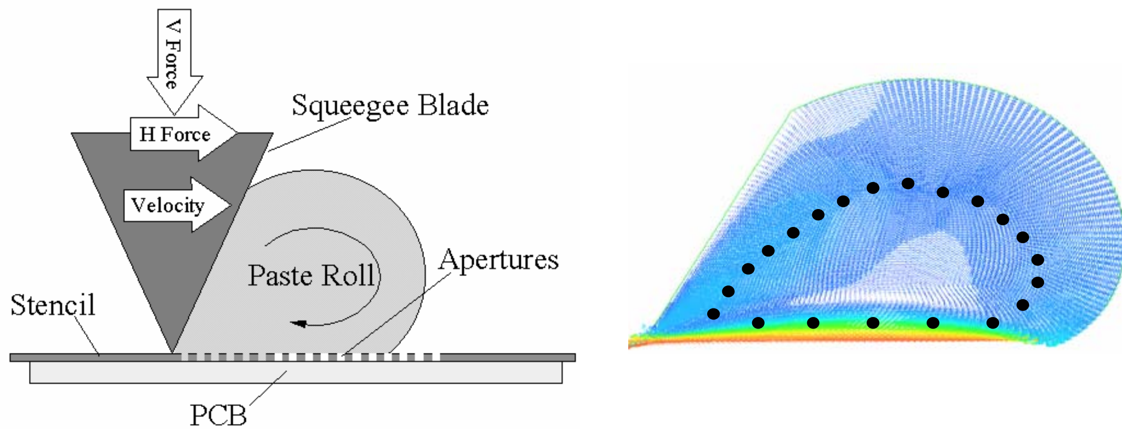

Figure 4, Results of solder paste flow using Non-Newtonian CFD

Pressure, velocity, shear rate and viscosity distributions can be determined throughout the paste material. Figure 5 shows the predicted pressure distribution in the paste along the stencil surface for a blade angle of 60 degrees and velocity of 1, 2, 3 and 4 cm/s. Comparisons are shown between SnPb and the ICA using the Cross Model, as detailed above. These distributions obtained along the base of the paste roll are of particular interest as the aperture filling process depends on the paste behaviour and material properties encountered in this region adjacent to the stencil surface.

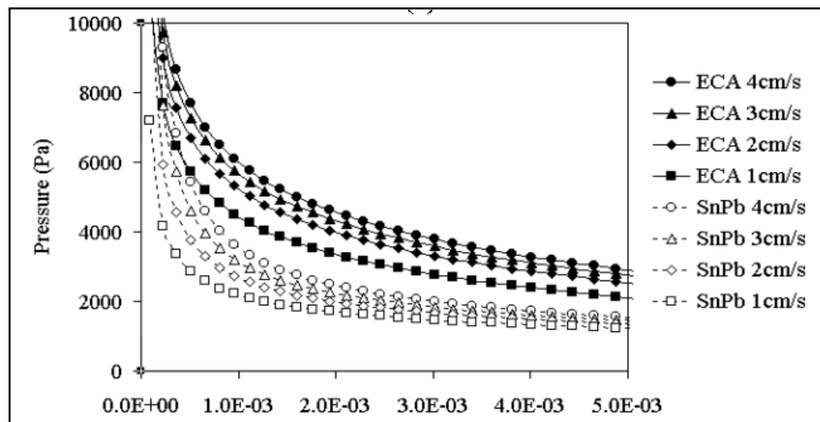

Figure 5, Pressure in paste material at different distances from blade tip.

Particularly large pressure gradients are observed in the region closest to the blade tip for both the tin-lead and ICA samples. There is a considerable difference in the pressure generated between the two samples. It can be seen that the pressure seen by the ICA is much higher than that observed by the tin-lead solder. This higher pressure with a lower viscosity in the blade tip region will help promote aperture fill.

Another area of interest with the new stencil design is the stress generated in the stencil due to its mounting and squeegee blade movement across its surface. Both the shear force, due to mounting the stencil in a frame, and the vertical force due to the pressure applied by the squeegee have been applied to a Finite Element Model representation of the stencil.

Figure 6 shows that the von-Mises stress in the stencil for both square and circular apertures. To minimize damage to the stencil and breakages between the apertures it is

important to ensure that the stress is kept to a minimum. The use of circular apertures reduces the stress by 20%.

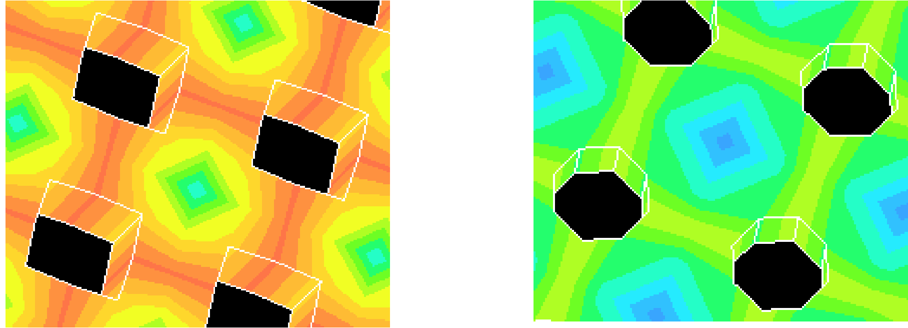

Figure 6, Von-Mises stress in the stencil for square and circular apertures.

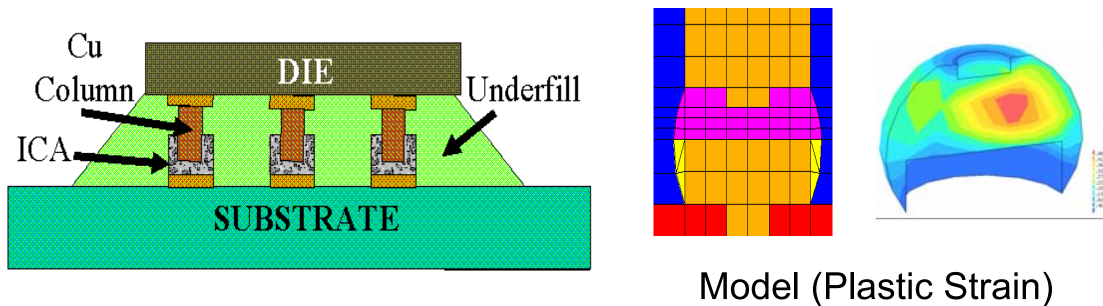

Figure 7, Assembled flip-chip using ICA and Cu Columns.

Themo-mechanical calculations [10] have been undertaken to investigate key process parameters that ensure higher reliability. Figure 7 shows the flip-chip assembly under investigation. Under thermal cycling the thermal mismatch in the materials will results in stress evolution and fatigue damage to the ICA joint. Examples of parameters investigated are underfill properties, volume of ICA paste deposited and wetting height of ICA along copper column. The damage parameter used in the calculations was the accumulated plastic strain in the solder paste. Higher values of this would increase the likelihood of crack initiation and propagation.

Simulations show that decreasing the CTE (20– 65ppm) of the underfill and increasing its Young's Modulus (1–5 GPa) decreases the plastic strain in the joint. Minimizing the amount of adhesive that wets the side walls of the copper column also helps reduce the plastic strain. The most important variable was the volume of adhesive deposited. Larger volumes producing a decrease in the plastic strain. Thinner substrates also helped reduce plastic strain in the adhesive and hence increase lifetime of the joint.

5. Print performance of the stencil

Initial print trials have been carried out using a small scale prototype stencil fabricated on a 3" wafer. As a stencil of this scale is too small to be mounted in a mesh frame, print trials of the Polysolder SE3001 isotropic conductive adhesive were initially carried out using hand printing. Hand printing does not allow consistent and repeatable parameters such as blade speed, angle and pressure to which the results can be correlated. Despite these disadvantages good quality prints were produced. Large arrays of conductive

adhesive were printed down to 50μm pitch as shown in figure 8. Good shape definitions were repeatedly achieved for circular & square apertures without cleaning the stencil.

The physical characteristics of the deposit (height and volume) were measured using a SEM and a Zygo NewView 5200 Scanning white light interferometry system. A linear variation of the deposits height of as a function of the aperture diameter was measured.

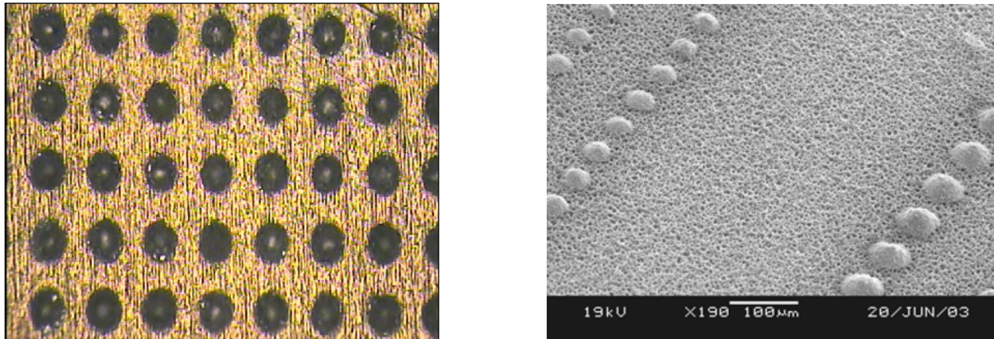

Figure 8, Hand printed Polysolder SE3001, the optical photograph shows 50μm deposits at 90μm pitch; the left column in the SEM shows 50μm deposits at 70μm pitch.

The deposits have the form of a cone unlike solder pastes deposits, which are typically flat topped. Adhesives tend not release completely from the aperture like solder pastes. In most cases more adhesive is left in the aperture than deposited onto the substrate. This artefact of the printing process is caused by the stencil acting like an array of micro dispenser tips. If the surface area of the aperture wall is greater than the surface area of the substrate exposed through the aperture, a small portion of the adhesive will remain on the substrate whilst the rest will remain in the stencil aperture [7]. For a 50μm thick stencil, this behaviour takes place for aperture diameters less than 200μm. If the surface area of the substrate is much greater than that of the aperture, the deposit released has a relatively flat top and equal roughly the thickness of the stencil. This simplified explanation does not take into account the wetting properties of the substrate and aperture sidewall which also play an effect in the fill and release characteristics of the aperture.

7.0 Conclusion

Novel stencils have been developed with extremely well defined aperture shapes and smooth sidewalls allowing thereby the successful printing of conductive adhesives at pitches as low as 50μm.

The viscosity of the solder pastes was found to be much higher compared to that of the ICAs. All samples showed a high degree of shear thinning when fitted to the Cross model. But as the shear rate increased the viscosity of all three samples dropped to a low value, which explains the good aperture filling observed during the printing process. However at lower shear rates the viscosity of each of the samples varied considerably which could have a large affect on the release process of the materials.

Pressure, velocity, shear rate and viscosity distributions have been calculated throughout the paste material using computational modeling techniques. During the printing process the pressure gradients seen by the ICA is much larger than that observed by the tin-lead solder. Modeling the stresses within the stencil after framing and during the printing process determined that the use of circular apertures reduces the stress built up by 20%.

In terms of reliability of the Microsystem package simulations show that decreasing the CTE (20 – 65 ppm) of the underfill and increasing its Young's Modulus (1 – 5 GPa) decrease the plastic strain in the joint. Also minimizing the amount of adhesive that wets the sidewalls of the copper column can also help reduce the plastic strain. The most important variable is the volume of adhesive deposited. Larger volumes produce a decrease in the plastic strain. Thinner substrates also aid in reducing the plastic strain in the adhesive and therefore increasing the lifetime of the joint.

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