Optimization and Characterisation of Bonding of Piezoelectric Transducers using Anisotropic Conductive Adhesive

G. Cummins, J. Gao, D.E. Watson, M.P.Y. Desmulliez
Multimodal Sensing and Micromanipulation Centre
School of Engineering and Physical Sciences
Heriot-Watt University
Edinburgh, UK, EH14 4AS
Email: G.Cummins@hw.ac.uk

R. McPhillips, S. Cochran
Medical and Industrial Ultrasonics Group
School of Engineering
University of Glasgow
Glasgow, UK, G12 8QQ

***Abstract*— Bonding technology using anisotropic conductive paste shows great promise to achieve the denser integration schemes that are required for the application of high resolution ultrasonic imaging. A design of experiments has been carried out to characterize and optimize a flip-chip bonding technology that utilizes a novel, magnetically aligned anisotropic conductive paste. This optimized process has the potential to implement more reliable and electrically conductive, fine pitch bonding for the production of high density ultrasound transducer arrays in needle devices.**

Keywords—anisotropic conductive adhesive; flip-chip bonding; high frequency ultrasound; design of experiments

I. Introduction

It is well known that higher frequency of operation of ultrasound transducers enables high resolution imaging. For example, an ultrasound transducer operating above 15 MHz is capable of achieving resolutions better than 200 µm [1]. Such resolutions can improve the accuracy of surgical interventions and are of increasing interest in medicine. However, higher frequency operation results in increased attenuation and consequently decreased penetration depth. The resulting low penetration depth of the image requires that the transducer be operated close to the tissue of interest, which is commonly achieved by packaging the high-frequency transducers directly into surgical tools. The limited real-estate available within these tools calls for miniaturization of the transducer and denser integration.

Whereas miniaturization of the transducers is possible with manufacturing techniques borrowed from the semiconductor industry, challenges exist in the creation of a reliable interconnection scheme, capable of producing high density electrical connections between the transducers and their external electronics. Commonly used interconnection technologies such as wire bonding are not feasible when working with arrays with a large number of elements. Moreover, in the case of transducers integrated into needles, the medical requirement of small gauges (G16 or above) prohibits wire bonding interconnect above a certain array size. The lack of suitable integration technology limited many earlier attempts at ultrasound transducers array in a needle to single element transducer [2] or using unsuitable packaging solutions [3].

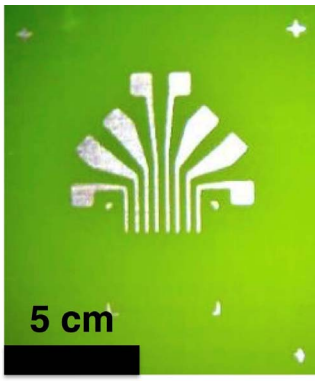

FIG. 1 IMAGE OF PCB TEST STRUCTURE

A more suitable integration solution, capable of meeting these constraints is the use of magnetically aligned, anisotropic conductive paste (ACP)[4] to electrically connect the sensing array electrodes to fine pitch, flexible printed circuit board (FPCB). ACPs are composed of fine electrically conductive particles uniformly dispersed in an adhesive matrix. The ACP forms electrical connections through the conductive particles, while the cured adhesive ensures the mechanical integrity and strength of the bond. This technology has many attractive properties, which include (1) isolation of the electrical connections from one another along the volume of the paste line, (2) reduced temperature curing compared to thermo-compression or eutectic bonding, (3) no flux residues and (4) no under filling [5], [6].

This paper builds upon previously reported work [7], [8] and describes the characterization and optimization process of that low temperature bonding technology for use in the production of miniaturized ultrasound systems to ensure increased interconnect yield. The development of a reliable integration technology suitable to produce a 15 MHz ultrasound transducer requires greater understanding of the underlying physics and the selection of process values that are

compatible with dimensional (<100 µm interconnect pitch) and manufacturing (low temperature, low pressure) constraints.

II. METHOD

A. Bonding Experiments

Initial experiments consisted of bonding two rigid PCB substrates, an example of which is shown in Fig. 1, forming a copper daisy chain electrical test structure with 200 µm track width and 200 µm pitch. An FR4 board substrate was used due to its low cost and wide applicability. The bond between the aligned PCBs is formed using an intermediate layer of ACP.

ZTACH™ low temperature, thermally cured ACP (Sunray Scientific, USA) [4] was manually dispensed at room temperature onto a 50 µm thick stencil before being forced through to the PCB surface. This ACP is a suspension of 1 µm diameter, silver-coated ferromagnetic beads within an epoxy resin. During curing of the epoxy, the beads align themselves along a uniform magnetic field applied perpendicularly to the PCB surface, forming thereby conductive tracks between the PCBs. Magnetic alignment for the desired conductive path is achieved using a magnetic jig with an average magnetic flux density of 2.7 mT.

Aligning and bonding of the test PCB was carried out using a MAT 6400 die bonder (MAT Ltd, Israel) operated in a flip-chip configuration mode. The bonded substrates were placed in a Gallenkamp Plus II oven (Gallenkamp, UK) and left to cure at 150°C for 15 minutes Though this temperature exceeds the Curie temperature of commonly used piezoelectric materials, it has been demonstrated that reducing the temperature to 80^{0}C and increasing the cure time to 3 hours results in a similar thermal budget such that it could be eventually used with piezoelectric transducer. The PCB stack is placed under the magnetic jig during curing.

24 hours after curing the resistance of the daisy chain test structures was measured via two-probe measurement with a handheld multimeter (Fluke, USA). Electrical continuity and resistance values along the conductive path formed between copper electrodes on opposite PCBs were checked and measured for all connections.

B. Design of Experiments

The use of a full factorial Design of Experiments (DoE) enables the identification of the sensitivity of the bonding process to alterations of various parameters and the effect of interactions between these parameters on the result. The bonding parameters have a substantial effect on interconnect reliability and conductance. The selection of optimal values for these parameters is complicated, as it can vary depending on the adhesive [9] and substrate properties.

Three factors - the bonding force, bonding duration and stencil slit width - were considered the most important based on past experience. The bonding force acting on the conductive particles has a significant effect on the contact area between the pads and the particles. If the bonding force is too low the conductive particles will not be able to form a continuous conductive path between the connecting pads. If the bonding force is too high the particles will fracture, leading to the disruption of the formation of a continuous electrical path. Ideally the force should be sufficient such that conductive particles should be deformed just before the metallic layers begin to fracture [6], [10]. The force at which this occurs has been shown to provide the largest contact areas, and therefore a lower average contact resistance. The value of this force varies, depending on factors such as particle size, material composition and others. The bonding force was controlled on the MAT 6400 die bonder through the use of an integrated, calibrated load cell. An equally important factor is the bonding duration, which refers to the period during which the ACP particles are subjected to the bonding force. Finally, changing stencil slit width causes increased paste area, which increases the chance of formation of conductive paths as well as mechanically stronger bonds. The fractional factorial DOE matrix is shown in Table I.

TABLE I: EXPERIMENTAL MATRIX AND RESULTS OF ACA OPTIMIZATION

					Copper Pads	
Exp. No.	*Parameter Set*	*Stencil Width (mm)*	*Bond. Force (g)*	*Bond. Time (s)*	$\bar{R}$ (Ω)	σ_R
1	7	1	300	10	2.6E+03	4.3E+03
2	2	0.3	300	50	2.5E+31	4.3E+31
3	4	1	100	10	1.6E+01	2.5E+01
4	6	1	100	50	5.0E+31	5.0E+31
5	1	1	300	50	5.0E+31	5.0E+31
6	3	0.3	100	50	8.5E-01	1.7E-01
7	5	0.3	300	10	5.0E+31	5.0E+31
8	8	0.3	100	10	8.5E+00	1.3E+01
9	3	0.3	100	50	2.5E+31	4.3E+31
10	5	0.3	300	10	2.7E+00	1.1E+00
11	2	0.3	300	50	5.0E+31	5.0E+31
12	6	1	100	50	9.3E-01	1.3E-01
13	7	1	300	10	1.7E+00	8.8E-01
14	8	0.3	100	10	5.0E+31	5.0E+31
15	4	1	100	10	5.3E+00	5.6E+00
16	1	1	300	50	2.5E+31	4.3E+31
17	5	0.3	300	10	2.5E+31	4.3E+31
18	8	0.3	100	10	1.1E+01	1.5E+01
19	7	1	300	10	1.3E+06	2.2E+06
20	3	0.3	100	50	2.5E+31	4.3E+31
21	1	1	300	50	1.4E+00	1.2E+00
22	2	0.3	300	50	3.5E+00	3.9E+00
23	6	1	100	50	7.5E+31	4.3E+31
24	4	1	100	10	1.4E+01	7.1E+00

The ideal bonding process should result in a reproducible and low contact resistance. The four measurements of the resistance taken during each experiment was used to calculate the average value and the standard deviation resulting from that combination of parameters. The main effects (1st order effects) and interaction matrix (2nd order effects) were calculated for both the average and standard deviation of the resistance as shown in Fig 2. Initial analysis of the results show that width of the bonding duration, then the stencil slit and bonding duration have a more dominant effect than the bonding force. The decrease in average resistance with reduced bonding time can be explained by also observing that reduction in bonding force and bond time decreases the standard deviation of the resistance. This could be attributed to the deformed conductive particles fracturing under loads of 300 g or large bonding times creating a poor and variable conductive path. Thereby a reduction in bonding time prevents fracture and ensures low and reproducible contact resistance,

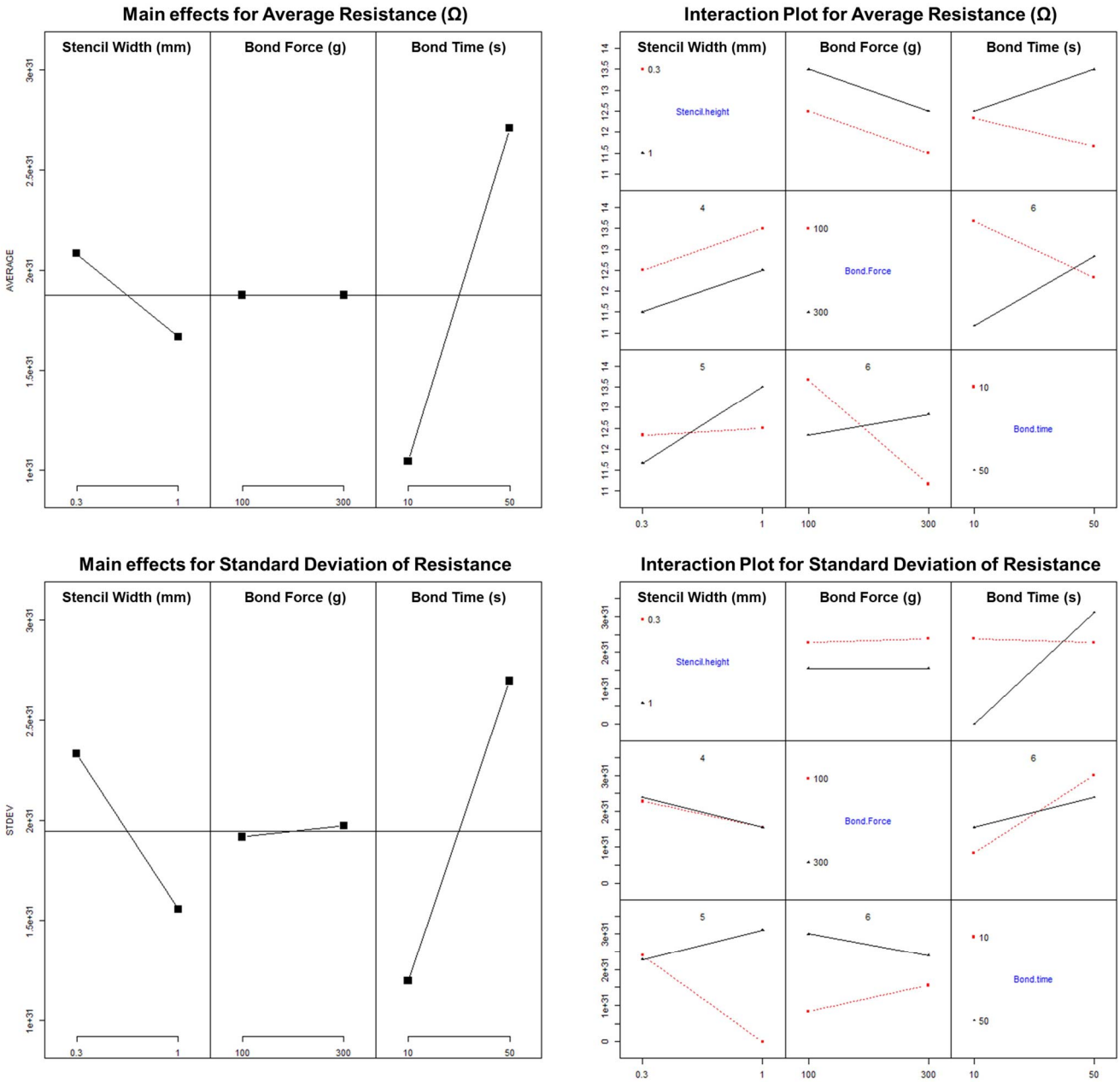

FIG. 2. MAIN EFFECT AND INTERACTION PLOTS FOR AVERAGE RESISTANCE VALUES AND STANDARD DEVIATION RESPONSES

which is expected due to the larger contact area between the intermediate film of paste and the electrical pads. Increasing stencil width results in a reduction in the average resistance.

The 2nd order effects for both standard deviation and average resistance shows no interaction between the bonding force and stencil widths. These parameters act independently of one another. However, both the bonding force and stencil width show interaction with the bonding time for both the average and standard deviation of the resistance. The strong interaction between bond force and time is not unexpected.

The interactions between stencil width and bonding time show that the process variability can be reduced using a short bonding time if a large stencil width is used, with changing bond time having a minimal 2nd order effect if a short stencil width is utilized. The use of a larger 50 s bonding time shows an increase in variability no matter what stencil width is used. This can also be explained by the increased risk of fracturing conductive particles when held under load for longer periods of time.

Analysis of the results of the experimental matrix showed that, for a bonding force of 100 g, stencil width of 1 mm and bonding time of 10 s, a good conductive bond was consistently formed for all 72 measurements. The mean electrical resistance of this bond between the copper electrodes was measured to be approximately 12 Ω, this resistance is an order of magnitude greater than expected but it may be attributed to the presence of a thin layer of oxide on the copper surface. The good

reproducibility and low resistance achieved with this set of parameters agrees with what has been observed from the main effect and interaction plot matrix for both the average and standard deviation values of the resistance.

III. CONCLUSION

This initial DOE analysis of the effect of process parameters such as bonding force, bonding time and stencil width on the quality and variability of a conductive bond generated between two copper electrodes and an intermediate layer of magnetically aligned ACP demonstrated an improvement of the yield of the bonds formed between piezoelectric, high frequency ultrasound transducers and flexible PCBs. The experimental matrix highlighted the sensitivity of this process with respect to the bonding time and amount of paste applied. This information will lead to more reliable integration processes, useful for the development of ultrasound transducer in needle applications.

ACKNOWLEDGMENT

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through the Programme Grant entitled "Sonopill: minimally invasive gastrointestinal diagnosis and therapy", grant no. EP/K034537/1 and EP/K034537/2. The authors also acknowledge the financial contribution of the UK Medical Research Council through its Confidence in Concept programme (MRC-CiC3/036) and the support of the Edinburgh & Lothian Health Foundation.

REFERENCES

[1] G. R. Lockwood, D. H. Turnbull, D. A. Christopher, and F. S. Foster, "Beyond 30 MHz - applications of high-frequency ultrasound imaging," *IEEE Eng. Med. Biol. Mag.*, vol. 15, pp. 60–71, 1996.

[2] T. Irie *et al.*, "Tissue imaging using the transmission of 100-MHz-range ultrasound through a fused quartz fiber," in *IEEE International Ultrasonics Symposium, IUS*, 2013, pp. 2010–2013.

[3] A. L. Bernassau *et al.*, "Microfabrication of electrode patterns for high-frequency ultrasound transducer arrays," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 8, pp. 1820–1829, 2012.

[4] Sunray Scientific, "Sunray Scientific Website." [Online]. Available: http://www.sunrayscientific.com/. [Accessed: 22-Aug-2017].

[5] M. J. Yim, Y. Li, K. Moon, K. W. Paik, and C. P. Wong, "Review of Recent Advances in Electrically Conductive Adhesive Materials and Technologies in Electronic Packaging," *J. Adhes. Sci. Technol.*, vol. 22, no. 14, pp. 1593–1630, 2008.

[6] Y. C. Lin and J. Zhong, "A review of the influencing factors on anisotropic conductive adhesives joining technology in electrical applications," *J. Mater. Sci.*, vol. 43, no. 9, pp. 3072–3093, 2008.

[7] G. Schiavone *et al.*, "A highly compact packaging concept for ultrasound transducer arrays embedded in neurosurgical needles," *Microsyst. Technol.*, pp. 1–11, 2016.

[8] G. Schiavone *et al.*, "Advanced electrical array interconnections for ultrasound probes integrated in surgical needles," *Proc. 16th Electron. Packag. Technol. Conf. EPTC 2014*, pp. 88–93, 2014.

[9] C.-M. Lin, "Effects of Pad Array Dimensions and Misalignment Offsets on Optimal Fraction of Conductive Particles in Anisotropic Conductive Film Packages," *IEEE Trans. Device Mater. Reliab.*, vol. 13, no. 1, pp. 301–309, Mar. 2013.

[10] Y. C. Lin and X. Chen, "Reliability of Anisotropic Conductive Adhesive Joints in Electronic Packaging Applications," *J. Adhes. Sci. Technol.*, vol. 22, no. 14, pp. 1631–1657, 2008.