IMPACT
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Evaluation of Tensile Strength of Copper-Cored Lead-Free Solder Joints in Air, Distilled Water, and NaCl Solution Using Testing Device with Permanent Magnets

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ABSTRACT

Solder joints have been used for electric connections in many electric devices. Since the electric devices are subjected to various loadings such as static, cyclic, and thermal stresses, the evaluation of solder joint strength under these conditions is necessary to guarantee the safety of electric devices. In addition, the electric devices are extending their application field and are used in corrosive conditions such as high humid and saline environments. The strength of solder joints under these conditions is also important. In this paper, tensile tests of copper-cored lead-free solder ball and nickel rod joints were carried out in air, distilled water, and salt water environments using a unique tensile testing device with permanent magnet. The joint strength and fracture behavior were discussed.

INTRODUCTION

As an increasing number of electric components have been used in automotive, aerospace, maritime, and defense applications, their reliability verification under harsh thermal and environmental conditions is becoming more and more important. In flip chip packages, the gap and print circuit board (PCB) are usually filled with underfill materials to increase their mechanical properties and to protect the package from outer environments. However, it is suggested that the underfill materials absorb moisture and corrosion media [1]. Therefore, solder joints must be resistant to water and corrosive media, and the tests under these conditions have been performed intensely for lead-free solder balls of various compositions [2-6].

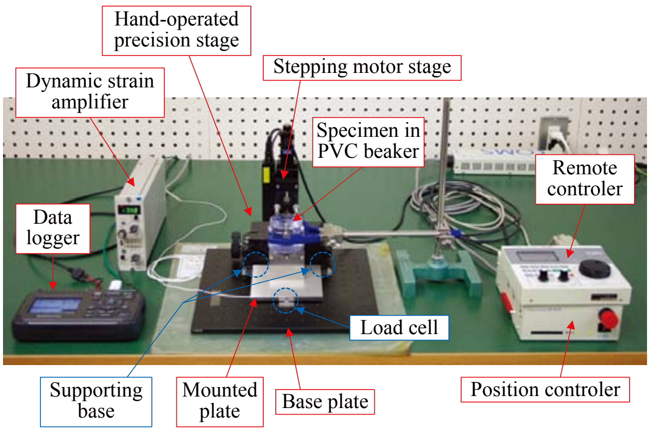

FIGURE 1. SETUP OF TENSILE TESTING DEVICE.

On the other hand, copper cored-solder balls have been developed as a potential candidate used in coming microelectronic packages with very fine ball pitch. Copper cores in solder balls achieve a stable standoff distance of packages during reflow process and thermal cycling in actual use. Higher resistance to electromigration and better electrical and thermal conductivities compared to conventional solder balls are also pointed [7-9]. But the investigation on their joining strength is still insufficient and the effect of water and corrosive environments on the strength has scarcely been discussed.

In this paper, tensile tests of copper-cored lead-free solder ball and nickel rod joints were carried out in air, distilled water, and NaCl solution using a unique tensile testing device with permanent magnet [10]. The joint strength and fracture behavior were discussed.

TENSILE TEST PROCEDURES

Tensile Testing Device Using Permanent Magnet

A tensile testing device used in this study is shown in Fig.1. The device was specially developed for tensile tests in air, water, and various solutions by the authors [10]. Since tensile force to the specimen is remotely generated by magnetic force, tests in beaker filled with liquid can be performed easily by the device. The device is composed of a square base plate of aluminum, a mounted plate of SUS304 austenitic stainless steel with five embedded neodymium magnet plates, a movable stage giving a displacement to specimen, and a hand-operated precision stage. The movable stage is located above the mounted plate and driven by a high precision stepping motor stage PM40B-25Z, which is controlled by position controller CP-310 and remote controller CP-3R produced by COMS Co., Ltd. A hand-operated precision stage of pantograph mechanism LJA-80133 produced by Sigma Koki Co., Ltd. is set under the stepping motor stage for coarse positioning of the movable stage. For tests in distilled water and NaCl solution, a colorless and transparent polyvinyl chloride (PVC) beaker is set with a three-finger holder of SUS304 austenitic stainless steel and its support stand. Compression load cell produced by Tokyo Sokki Kenkyujo Co., Ltd. (Tokyo Measuring Instruments Laboratory Co., Ltd.) is set under the mounted plate which works as one of three supports and the compressive load is monitored during the test through dynamic strain amplifier AS1103 produced by NEC Avio Infrared Technologies Co.,

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Ltd. USB microscope SG-200PC produced by Shodensha, Inc. is used for in-situ observation of the specimen.

Calibration of Tensile Load

The applied load or force acting to the solder joint, F [N], is obtained by a transformation of compressive load measured by the load cell, R_{LC} [N]. Their relationship is roughly derived as

$$R_{LC} = 0.310F - 8.065, \tag{1}$$

by a simple beam theory [10]. In order to obtain more accurate relationship, the experimental calibration was performed by putting cylindrical weights of nonmagnetic austenitic stainless steel manufactured by Sinko Densi Co. Ltd. on the top of magnet plate. The obtained results are shown in Fig.2. The abscissa M is the weight of cylindrical weight. Very similar results were obtained for five trials. The following Eq.(2) was obtained by the least-square method for average values of R_{LC} at each weight M,

$$R_{LC} = -0.315M - 7.706. \tag{2}$$

Eq.(3) was obtained by solving Eq.(2) for F (=$-M$), and used to evaluate the applied load F during tensile tests.

$$F = (-M) = \frac{R_{LC} + 7.706}{0.315}. \tag{3}$$

Copper-Cored Lead-Free Solder Balls

Copper-cored Sn-3.5Ag-0.75Cu lead-free solder balls with a total diameter of 440 µm manufactured by Hitachi Metals, Ltd. were used. Diameter of the copper core is 320 µm and the core is nickel-plated by a thickness of 2 µm. Soldering flux RM-5, which is an RMA (Rosin Mildly Activated)-type smooth flux manufactured by Nihon Superior Co., Ltd., was used for joining the solder ball to upper and lower center rods of pure nickel. The joining was performed by heating and the maximum temperature measured on the surface of specimen fixture was between 526 K and 531 K depending on the specimen. Finally, the specimen with nickel and magnet disks shown in Fig.3 was prepared for each test.

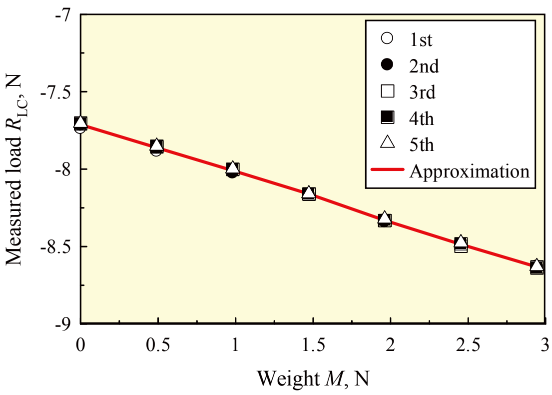


FIGURE 2. RELATIONSHIP BETWEEN LOAD MEASURED BY LOAD CELL AND WEIGHT PUT ON THE TOP OF MAGNET PLATE.

Stage Displacement and Environment

Tensile tests were conducted in air, distilled water, and 3.5wt.% NaCl solution. Since bottom end of the specimen is not chucked, tests were easily prepared by inserting the specimen into PVC beaker filled with liquid. Three specimens were prepared for each of three environments (in air, distilled water, and 3.5wt.% NaCl solution). They are called DA-*i*, DW-*i*, and DSW-*i* (i=1 to 3), respectively.

Tensile tests were carried out by controlling the descending displacement of movable stage, as schematically shown in Fig.4. The decrease in the distance between the magnet disks at the bottom of specimen and the magnet plates embedded in magnet fixture brings the increase in the magnetic force, and then the tensile load acting to

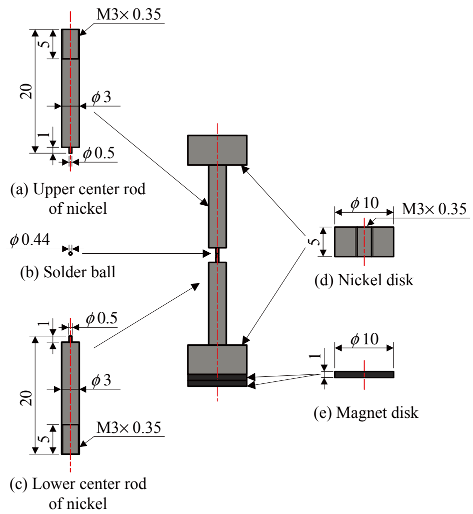


FIGURE 3. DETAIL OF A SPECIMEN.

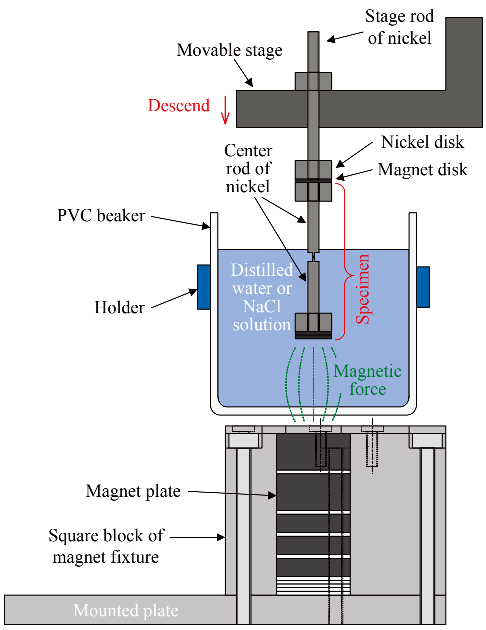


FIGURE 4. INCREASING IN TENSILE LOAD AND MAGNETIC FORCE BY DESCENDING THE MOVABLE STAGE.

the specimen increases. The descending rate of movable stage was kept constant at 0.2 mm/s for all the tests. The test was continued until the solder ball was disjoined.

RESULTS OF TENSILE TESTS

Fracture of Solder Ball Joint

Disjoined solder ball joints of specimens DA (in air), DW (in distilled water), and DSW (in NaCl solution) are shown in Fig.5. There is no significant difference in the appearance between solder balls fractured in air, distilled water, and NaCl solution. However, fracture always occurred on the lower joint interface of solder ball and center rod of pure Ni. The reason for the consistent lower interface fracture may be attributed to the vertical setting of the specimen during the heat for joining. Vertical asymmetry such as small differences in joining area, soldering flux distribution between the upper and lower joints, and the position of copper core in the solder ball, and the vertical temperature distribution during cooling after the peak temperature, may cause the consistent fracture at the lower interface.

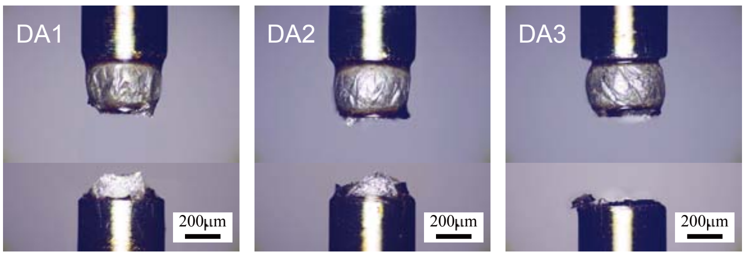
Change in Load with Time

Changes in applied load, F, during tensile tests are shown in Fig.6. While there is a small difference in the initial load due to the small difference in specimen positioning, load F increases with time t along a similar path. The increasing rate of load F slightly increased with time under constant descending rate of movable stage. The downwardly convex F-t curve is reasonable considering that the magnetic force between two magnets increases inversely proportional to the square of inter-magnet distance.

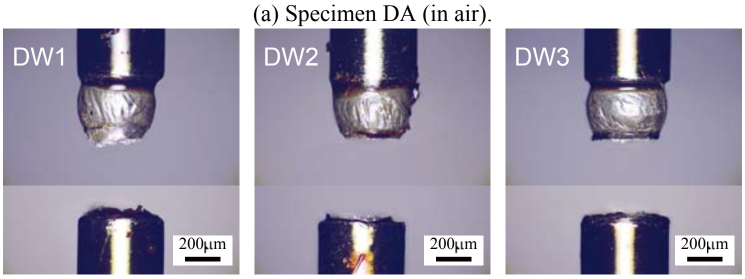
Focusing on the load at fracture, relatively large difference is found in tests for specimen DW. Fracture load for specimen DW2 was lower than those for the other specimens.

Fracture stress for each specimen is shown in Fig.7, which was evaluated from the load at fracture shown in Fig.6 and the area of fracture surface obtained by optical microscope after the tensile test. The fracture stresses ranges between 35 and 55 MPa for all the specimens except DW2. The almost constant fracture stress in all environments suggests that the environment effect was small. In the present study, time to fracture was shorter than 80 s, which is not long enough to show corrosion effect to tensile fracture.

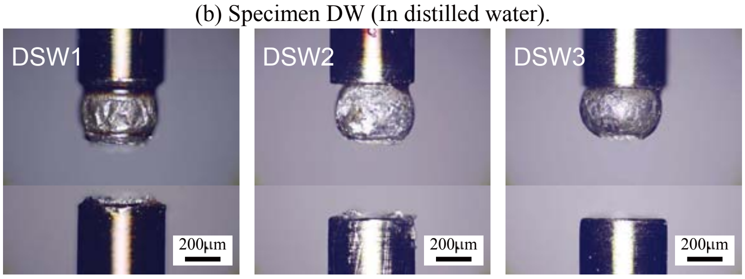
Concerning the low fracture stress in DW2, no clear reason was



(a) Specimen DA (in air).

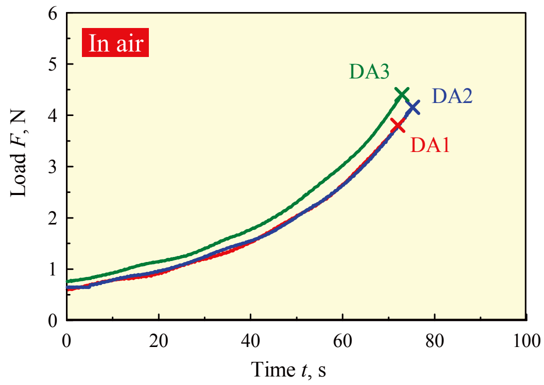


(b) Specimen DW (In distilled water).

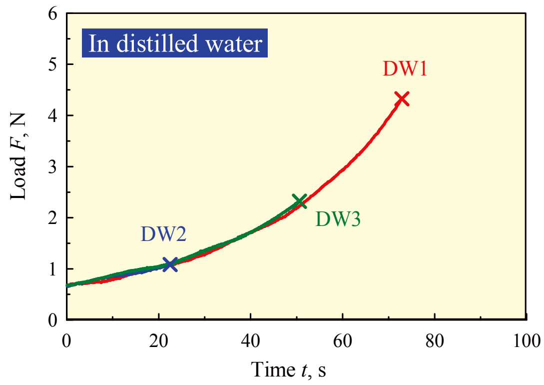


(c) Specimen DSW (in NaCl solution).

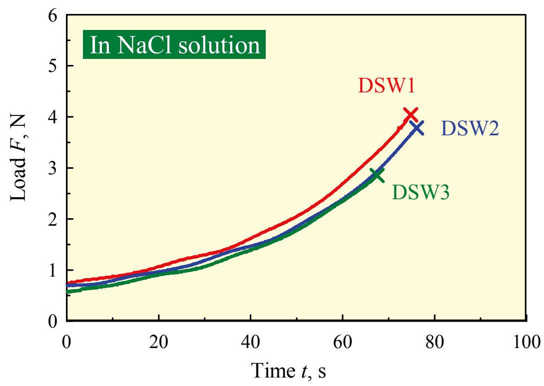
FIGURE 5. FRACTURED COPPER-CORED SOLDER BALL JOINT.



(a) Specimen DA.



(b) Specimen DW.



(c) Specimen DSW.

FIGURE 6. CHANGE IN LOAD WITH TIME.

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found. There was no significant difference in fracture surface observed by scanning electron microscope (SEM) with the other specimens. Its candidate reasons are 1) initial voids introduced during the heating for joining, and 2) effect of soldering flux amount around the interface. The initial voids may decrease the apparent tensile strength. However, it was difficult to discriminate those voids from plastic voids initiated by ductile fracture on the fracture surface. Meanwhile, large amount of soldering flux strengthen the interface. If the joint interface is covered by relatively large area of soldering flux, the apparent strength becomes large. Because the fracture surface of soldering flux is not counted for evaluation of fracture stress. Its accurate evaluation was difficult since a part of soldering flux was spread out at fracture. On the contrary, if the amount of soldering flux is uneven around the joint interface, it may cause bending moment on the interface and decreases the apparent strength. By performing more tests, the reason should be confirmed.

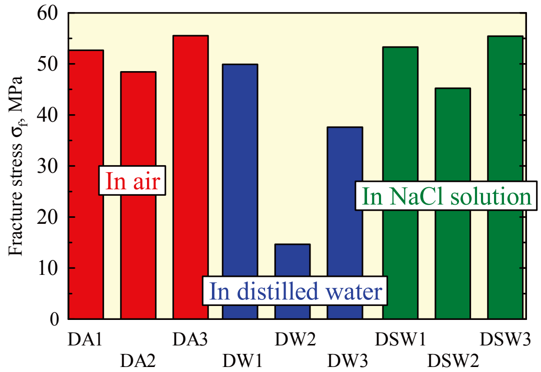

FIGURE 7 FRACTURE STRESS.

CONCLUSIONS

Tensile tests of copper-cored Sn-Ag-Cu lead-free solder ball joints were carried out in air, distilled water, and NaCl solution using a unique testing device. The small solder ball was set between two thin pure nickel rods and joined by heating. Since the tensile testing device uses permanent magnet, tensile load can be given to the specimen set in transparent and colorless polymer beaker and the tests in various liquid becomes possible. The tests were successfully done for all the environments. The fracture stress was almost constant within a range of 35 and 55 MPa independent of the environment because of relatively short test time. One specimen tested in distilled water showed relatively low fracture stress. The reason for this scatter should be examined by increasing the number of tests and more detailed observation.

REFERENCES

[1] D. Li, P. P. Conway and C. Liu, "Corrosion Characterization of Tin-Lead and Lead Free Solders in 3.5 wt.% NaCl Solution," *Corrosion Science*, Vol. 50, Issue 4, 2008, pp.995-1004.

[2] C. Anderson and J. Liu, "Effect of Corrosion on the Low Cycle Fatigue Behavior of Sn-4.0Ag-0.5Cu Lead-Free Solder Joints," *International Journal of Fatigue*, Vol. 30, Issue 5, 2008, pp.917-930.

[3] F. Rosalbino, E. Angelini, G. Zanicchi, R. Carlini and R. Marazza, "Electrochemical Corrosion Study of Sn-3Ag-3Cu Solder Alloy in NaCl Solution," *Electrochimica Acta*, Vol. 54, Issue 28, 2009, pp.7231-7235.

[4] U. S. Mohanty and K-L. Lin, "Electrochemical Corrosion Behaviour of Pb-Free Sn-8.5Zn-0.05Al-XGa and Sn-3Ag-0.5Cu Alloys in Chloride Containing Aqueous Solution," *Corrosion Science*, Vol. 50, Issue 9, 2008, pp.2437-2443.

[5] W. R. Osorio, J. E. Spinelli, C. R. M. Afonso, L. C. Peixoto and A. Garcia, "Microstructure, Corrosion Behaviour and Microhardness of a Directionally Solidified Sn-Cu Solder Alloy," *Electrochimica Acta*, Vol. 56, Issue 24, 2011, pp.8891-8899.

[6] W. R. Osorio, L. R. Garcia, L. C. Peixoto and A. Garcia, "Electrochemical Behavior of a Lead-Free SnAg Solder Alloy Affected by the Microstructure Array," *Materials and Design*, Vol. 32, Issue 10, 2011, pp.4763-4772.

[7] Y. Kim, H. Choi, H. Lee, D. Shin, J. Moon and H. Choe, "Fracture Behavior of Cu-Cored Solder Joints," *Journal of Materials Science*, Vol. 46, Issue 21, 2011, pp.6897-6903.

[8] Y. Kim, H. Choi, H. Lee, D. Shin, J. Cho and H. Choe, "Improved Reliability of Copper-Cored Solder Joints under a Harsh Thermal Cycling Condition," *Microelectronics Reliability*, Vol. 52, Issue 7, 2012, pp.1441-1444.

[9] K. Uenishi, Y. Kohara, S. Sakatani, T. Saeki, K. F. Kobayashi and M. Yamamoto, "Melting and Joining Behavior of Sn/Ag and Sn-Ag/Sn-Bi Plating on Cu Core Ball," *Materials Transactions*, Vol. 43, No.8, 2002, pp.1833-1839.

[10] N. Tada and H. Masago, "Remotely-Controlled Tensile Test of Copper-Cored Lead-Free Solder Joint in Liquid Using Permanent Magnet", *The 8th International Microsystems, Packaging, Assembly and Circuits Technology Conference Proceedings,* 2013, pp.372-375.