Electroless Nickel / Electroless Palladium / Immersion Gold Plating Process for Gold- and Aluminum-Wire Bonding Designed for High-Temperature Applications

Kuldip Johal, Sven Lamprecht and Hugh Roberts
Atotech Deutschland GmbH, Berlin, Germany
Atotech USA Inc., Rock Hill, SC, USA
kjohal@atousa.com; sven.lamprecht@atotech.com; hroberts@atousa.com

ABSTRACT

This paper summarizes the results of qualification testing of the Electroless Nickel / Electroless Palladium / Immersion Gold (Ni/Pd/Au) process as it may be applied for use in high-temperature functional applications. The effects of exposure to heated, high humidity environments were also examined, in addition to the impact of extended thermal cycling.

The survivability of the Ni/Pd/Au deposit was studied for both gold wire (30-µm gauge) and aluminum wire (32-µm gauge) bonding under the following test parameters:

- *Dry heat aging at 125°C and 150°C*
- *Relative humidity up to 85% at 85°C*
- *Exposure times up to 2000 hours*
- *Thermo cycling (- 40°C / +125 °C) for 2000 cycles.*

The reliability of the wire bonds was characterized by both wire-pull testing and visual inspection. With respect to gold wire bonds, it was found that regardless of environmental exposure the wire pull force remained unchanged during the testing period. Conversely, for aluminum wire bonds the pull force under dry-heat aging decreased initially and then stabilized.

During this qualification of the Ni/Pd/Au process, an examination of ball shear strength of BGA solder joints during thermal aging was also conducted. The results of these tests with eutectic Sn/Pb solder after thermo-cycling will be presented in a subsequent paper.

Key words: Nickel / Palladium / Gold, ceramics, Gold wire, Aluminum wire, bonding

BACKGROUND

The continuously increasing use of electronic devices at higher operation temperatures is placing technological demands on both the components as well as the printed wiring board. Within the automotive segment, critical under-hood applications (i.e. engine and braking controls) subject the electronic device to extended exposure at high temperatures and extreme temperature variations. Often, the preferred PWB substrate choice for such applications is a ceramic material, which is then printed with gold, silver or silver/palladium paste (Fig 1). For the latest technical demands, the most difficult problem is to find a suitable surface offering reliability in terms of gold and aluminum wire bonding, conductive adhesive printing dimensions, solderability and its ability to meet further decreasing line and space dimensions as needed.

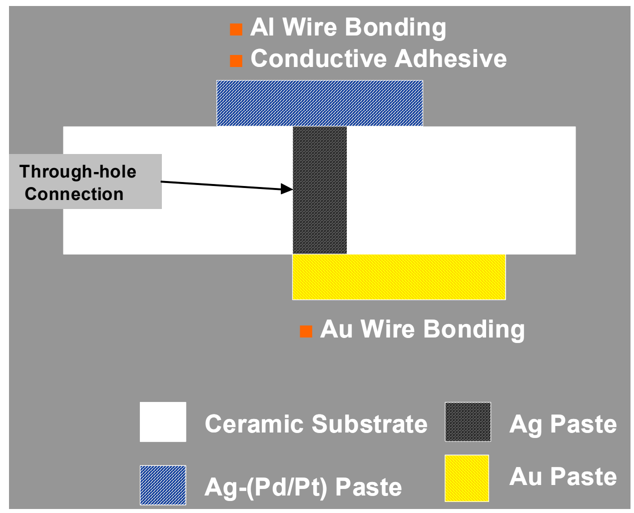
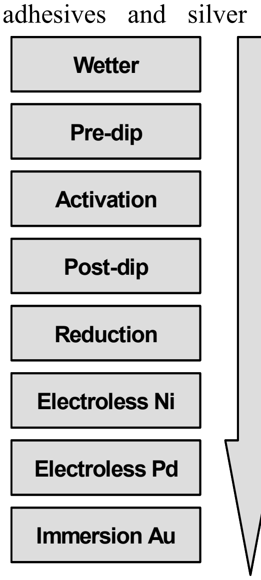


Fig 1. Typical application for thick film on ceramic substrates (simplified)

Combining gold paste screen printing with conductive adhesives and silver or silver/palladium paste screen printing most of the demands could be fulfilled. But this results in a relatively complicated manufacturing process. A more cost-effective manufacturing method must be considered as a replacement for gold paste printing on ceramic substrates, where gold paste deposit thicknesses of up to 30 µm are often required depending on the application.



As a final finish, the proposed electroless nickel / electroless palladium / immersion gold (Ni/Pd/Au) plating process meets the technical requirements while offering the possibility for cost reduction. The process provides a selectively deposited Ni/Pd/Au directly on the pre-treated ceramic substrates. When combined with stencil printing of silver paste, Ni/Pd/Au can be used for high-temperature applications in mass production. Due to the nature of the process, the initial screen-printed paste underlying the Ni/Pd/Au must first be activated, enabling the deposition of an autocatalytic Nickel-Phosphorous (7-9 % P by wt.) layer. This deposit is then covered by a thin autocatalytic-plated pure palladium layer, containing 99.99% Pd. Finally, a "flash" layer of immersion gold (30-50 nm) is deposited.

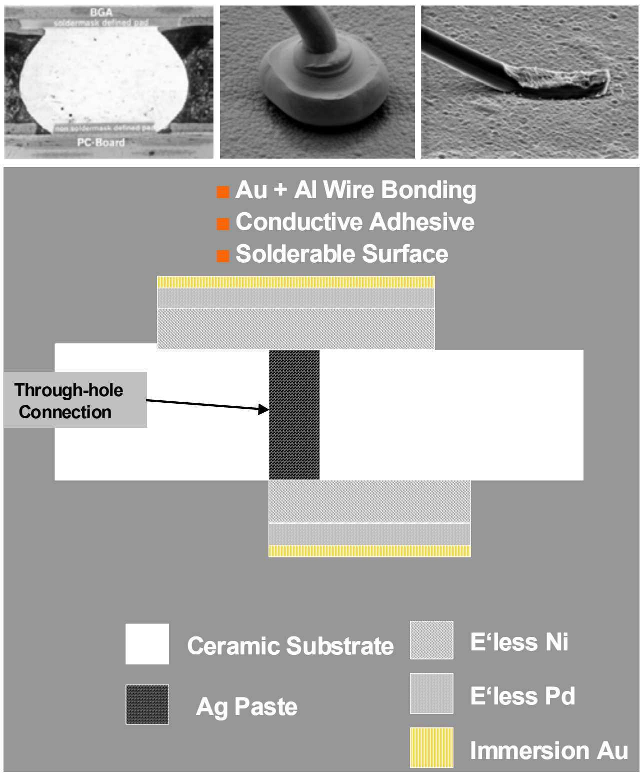


Fig. 2 Application of Ni/Pd/Au for multi-functional finish of ceramic material

This layer combination of pure palladium and gold enables both aluminium- and gold-wire bonding on the same surface, thus eliminating the need for two different screen-printed pastes. All surfaces of the printed structures are fully covered, including sidewalls. In addition to eliminating the use of costly gold paste, this technique eliminates any capital costs for electroplating and photo-lithography equipment.

EXPERIMENTAL PROCEDURE

To examine the suitability of the Ni/Pd/Au surface for combined aluminum- and gold-wire bonding applications, testing was performed to simulate various functional and environmental conditions. For testing purposes, the layer composition was as presented in Table 1:

Table 1 – Ni/Au/Pd Deposit Specifications

Metal Deposit	Type	Thickness
Nickel	Electroless 8.5% P by wt.	6.0 µm
Palladium	Electroless 99.9% pure	0.2 µm
Gold	Immersion	0.06 µm

All thicknesses were measured by XRF technique, using thickness standards that were verified by wet analytical method ICP-AA.

To establish the parameters that would be used for all wire bonding, Ni/Pd/Au samples were pre-aged for three hours at 150 °C. Bonding results for these samples were compared to results from "as is" samples (i.e. no heat aging).

Specifications and conditions for gold-wire bonding and aluminum-wire bonding are shown in Table 2 and Table 3, respectively.

Table 2 – Gold Wire Bonding Specifications

Wire Supplier/Type	Hereaus / Au-Beta
Wire Diameter	30 µm
Wire Pull Strength (max)	11-15 cN
Elongation	3-6 %
Wire Bonder Make/Model	K&S Model 4124
Bonder Operating Conditions	115 °C, 140 kHz
Bonding Capillaries	Micro Swiss 40472-0012-320 Flat-face design 8º face angle

Table 3 – Aluminum Wire Bonding Specifications

Wire Supplier/Type	MFD / AlSi1 (1% silica)
Wire Diameter	32 µm
Wire Pull Strength (max)	21-24 cN
Elongation	1-4 %
Wire Bonder Make/Model	Delvotec Model 6400
Bonder Operating Conditions	100 kHz

For each test procedure, 30 gold wires and 40 aluminium wires were bonded and pull-tested at mid-span. In addition, for gold wire, 30 wedge bonds were also pulled. Prior to aluminum-wire bonding, all Ni/Pd/Au layers were pre-aged for one hour at 150ºC. The pass-fail criteria used in the evaluation are presented in Table 4:

Table 4 – Wire Bond Test Criteria	
Parameter	**Test Pass Criteria**
Average pull force	> 50% of max. wire force
Standard deviation	< 15% of average force
Bonds strength < 6cN	None
Bond wedge lifts	None

Following fabrication of the bonds, extended aging and conditioning tests were performed to investigate pull force performance and failure modes. Table 5 presents specifications and conditions for established tests.

Table 5 – Bond Testing Specifications and Conditioning	
Temperature/Humidity Test Chamber	ESPEC / Model LHL-212
High Temperature Aging Tests	125°C and 150°C
Humidity Tests	85% RH, 85°C
Thermo-cycling Test Chamber	Voetsch Model VT 7012 S2
Thermo-cycling Tests	Min/Max: –40 / +125 °C (30-min dwell, 3-sec transfer)
Test Intervals (hours)	24/100/250/500/1000/2000
Pull Test Equipment	Dage / Model BT2400PC

Pull forces and fracture modes were recorded at the test intervals indicated in Table 5. Failure modes were investigated with the use of an optical stereo microscope.

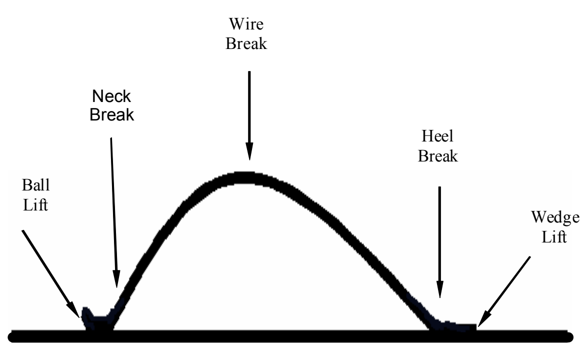


Fig. 3 Wire bond failure modes

GOLD WIRE BONDING RESULTS

The results of tests performed with gold wire bonding are summarized in Figures 4 through 8.

Test – Gold Bond Dry Heat Aging (125º)

Figure 4 shows the mean values and standard deviations of the pull forces required to break the wire bonds in the 125ºC dry-heat conditioning test. As shown, all values exceed the pass criteria range of 5.5 to 7.5 cN (i.e. 50% of the unbonded gold wire tensile strength). Additionally, the standard deviation is well within the pass criteria of less than 15% of average force.

Test Results:

- Average "As is" Pull Force = 10.9 cN
- Average Pull Force (after 100 hrs) = 12.6 cN
- Average Pull Force after 2000 hours = 10.6 cN

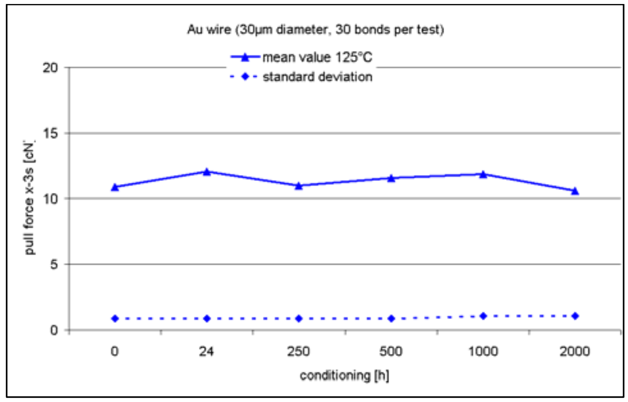


Fig. 4 Average wire pull forces for gold wire bonds following heat conditioning (125°C)

Test – Gold Bond Dry Heat Aging (150º)

The results of the gold-wire bond tests performed after 150º dry-heat aging are summarized in Figure 5. Again, all pass criteria are achieved.

Test Results:

- Average "As is" Pull Force = 10.9 cN
- Average Pull Force (after 1000 hrs) = 13.4 cN
- Average Pull Force after 2000 hours = 11.7 cN

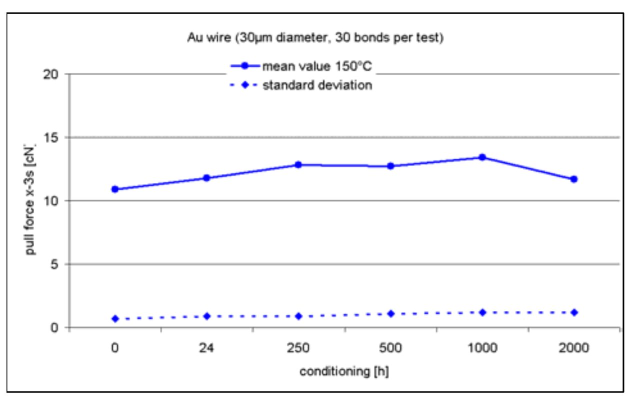


Fig. 5 Average wire pull forces for gold wire bonds following heat conditioning (150°C)

Test – Gold Bond Heat and Humidity Conditioning
Figure 6 shows the mean values and standard deviations of the pull forces required to break the wire bonds in the heat (85°C) and humidity (85%RH) conditioning test. All pass criteria set forth in Table 4 are again achieved.

Test Results:

- Average "As is" Pull Force = 10.9 cN
- Average Pull Force (after 100 hrs) = 15.8 cN
- Average Pull Force after 2000 hours = 11.2 cN

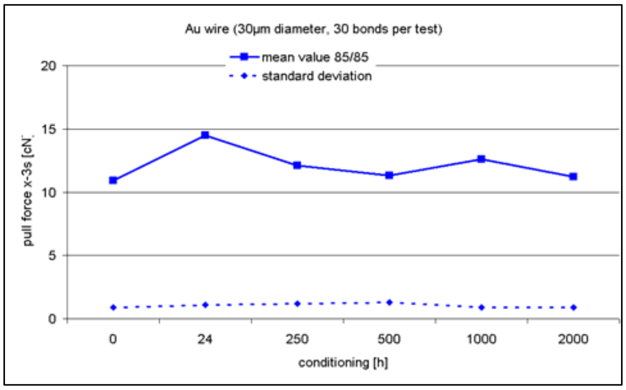


Fig. 6 Average wire pull forces for gold wire bonds following heat (85°C) and humidity (85%) conditioning

Test – Gold Bond Thermo-Cycle Conditioning
The results of the gold-wire bond tests performed after thermo-cycling are summarized in Figure 7. Thermo-cycling conditions are described in Table 5. Again, all pass criteria are achieved.

Test Results:

- Average "As is" Pull Force = 10.9 cN
- Average Pull Force (after 500 TCs) = 12.6 cN
- Average Pull Force (after 1000 TCs) = 12.6 cN
- Average Pull Force after 2000 hours = 11.7 cN

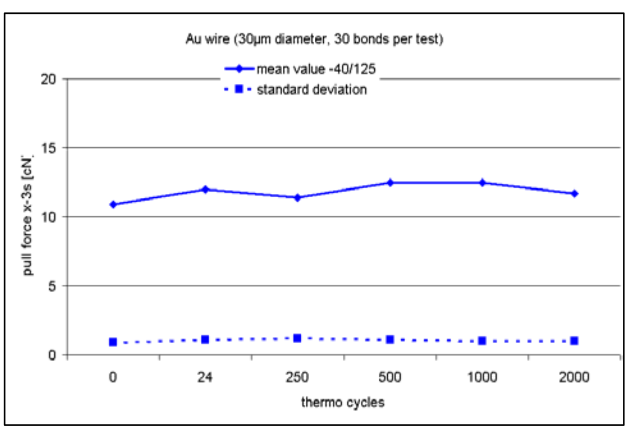


Fig. 7 Average wire pull forces for gold wire bonds following thermal cycling (-40ºC to 125ºC)

Gold Wire Bond Failure Analysis
The most dominant failure mode for gold-wire bonds in this study was neck-break above the ball. Failures related to the Ni/Pd/Au deposit (i.e. ball or wedge lifts) did not occur for gold-wire bonding. Even after 2000 hours of dry heat conditioning or 2000 thermal cycles, none of the gold wire bonds showed wedge lifts.

For the gold-wire bonds, second-bond heel breaks only occurred after 150°C aging, as seen in Figure 8. Other temperature, humidity or thermo-cycle conditioning did not result in any second-bond heel breaks. Interestingly, comparing the results in Figure 8 to Figure 5, the incidence of second-bond heel breaks at 150 °C conditioning did not affect the mean values for the maximum pull forces nor the standard deviation.

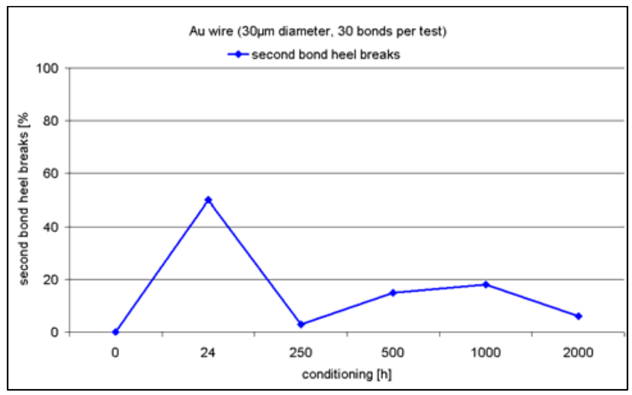


Fig. 8 Incidence of second-bond heel breaks for gold wire bonds following heat conditioning (150°C)

ALUMINUM WIRE BONDING RESULTS
The results of tests performed with aluminum wire bonding are summarized in Figures 9 through 14. As mentioned previously, all Ni/Pd/Au samples were baked for one hour at 150°C prior to bonding.

Test – Aluminum Bond Dry Heat Aging (125º)
Figure 9 shows the mean values and standard deviations of the pull forces required to break the wire bonds in the 125ºC dry-heat conditioning test. As shown, not all values achieved the pass criteria range of 10.5 to 12.0 cN (i.e. 50% of the unbonded aluminum wire tensile strength), although only nominally below the range. However, after 250 hours of conditioning, the average values are only slightly below the lower pass limit. The standard deviation is well within the pass criteria of less than 15% of average force.

Test Results:

- Average "As is" Pull Force = 18.0 cN
- Average Pull Force (after 250 hrs) = 10.3 cN
- Average Pull Force after 2000 hours = 10.1 cN

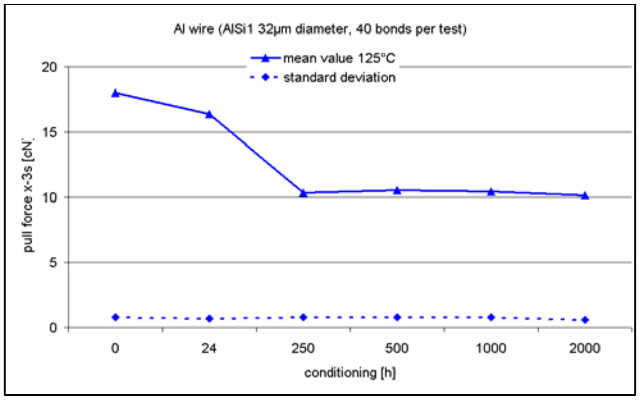


Fig. 9 Average wire pull forces for aluminum wire bonds following heat conditioning (125°C)

Test – Aluminum Bond Dry Heat Aging (150º)
The results of the aluminum-wire bond tests performed after 150º dry-heat aging are summarized in Figure 10. After 250 hours of conditioning, the average pull force remained marginally below the lower range of the pass criteria (10.5 cN).

Test Results:

- Average "As is" Pull Force = 18.0 cN
- Average Pull Force (after 24 hrs) = 11.7 cN
- Average Pull Force after 2000 hours = 9.2 cN

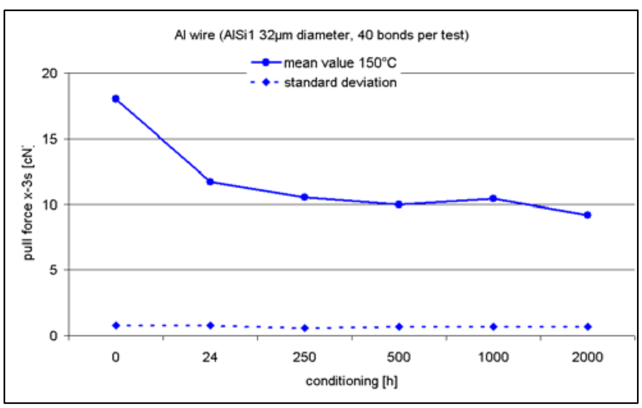


Fig. 10 Average wire pull forces for aluminum wire bonds following heat conditioning (150°C)

Test – Aluminum Bond Heat and Humidity Conditioning
Figure 11 presents the mean values and standard deviations of the pull forces required to break the aluminum wire bonds in the heat (85°C) and humidity (85%RH) conditioning test. All pass criteria set forth in Table 4 are again achieved.

Test Results:

- Average "As is" Pull Force = 18.0 cN
- Average Pull Force (after 24 hrs) = 18.7 cN
- Average Pull Force after 2000 hours = 11.7 cN

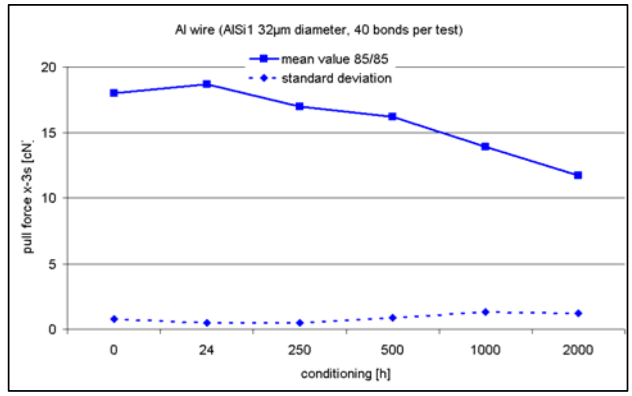


Fig. 11 Average wire pull forces for aluminum wire bonds following heat and humidity conditioning

Test – Aluminum Bond Thermo-Cycle Conditioning
The results of the aluminum-wire bond tests performed after thermo-cycling are summarized in Figure 12. Thermo-cycling conditions are described in Table 5. Results of pull forces after 1000 thermo cycles averaged just marginally less than the lower limit of the pass criteria, achieving nearly 10 cN.

Test Results:

- Average "As is" Pull Force = 18.0 cN
- Average Pull Force (after 500 TCs) = 11.7 cN
- Average Pull Force after 2000 hours = 9.7 cN

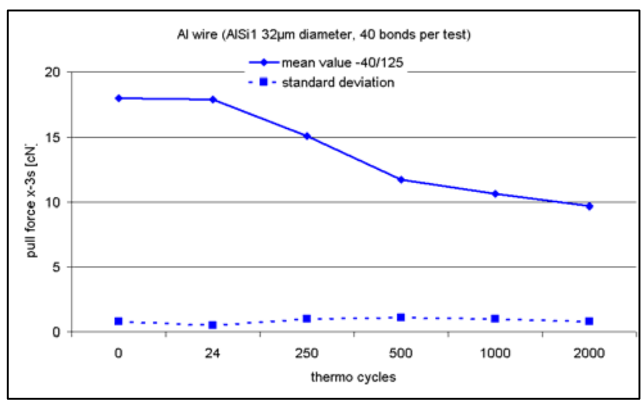


Fig. 12 Average wire pull forces for gold wire bonds following thermal cycling (-40ºC to 125ºC)

Aluminum Wire Bond Failure Analysis
After 2000 hours of dry-heat conditioning or 2000 thermal cycles, none of the aluminium wire bonds exhibited wedge lifts. Although average pull forces during the dry heat treatment were just marginally below the pass criteria (i.e. 50% of the unbonded aluminum wire tensile strength), none of the tests resulted in pull forces less than 6 cN. There was no measurable degradation at the interface of bond and pad. It was previously reported that intensive voiding can occur for aging at temperatures of 400 °C for more than 100 hours. However, for aluminum-wire bonding, the Ni/Pd/Au process is production-proven to be reliable for temperatures below 200 °C.

Temperatures of 150 °C will change the physical properties of the aluminum wire after 24 hours, resulting in a decrease in hardness/strength to 2/3 of 'as is' (see Fig. 10 at 24 hours). As expected, at lower temperatures (i.e. 125 °C), these diffusion controlled reactions require additional time (see Fig 9 at 250 hours). While limited to heel breaks or wire breaks, the average pull force of the aluminum wires still decreases to approximately 10 cN. This decrease in tensile strength is strongly influenced by time and temperature, which is a well-known phenomenon with the use of aluminum wires containing even one- or two-percent silica, such as that used in the test (MFD AlSi1). During the manufacturing process of AlSi1 wires the crystal structure is manipulated through welding and temperature treatment. Through diffusion promoted by heating, the smallest silicon precipitations within the aluminium matrix will merge into larger crystals, thereby changing the hardness and strength characteristics of the wire. As such, the structure of the AlSi1 wires (as supplied) has been strongly influenced by the dry heat conditioning of the specimen in these investigations.

As Figure 13 shows, after 500 hours of high-humidity conditioning (85/85) second wedge lifts occurred in nearly twenty percent of the cases. The previously mentioned temperature-controlled silica diffusion reaction that lowers the mechanical hardness/strength is less of a factor at 85 °C compared to 125 °C or 150 °C. This can be seen by comparing the results in Figure 11 to those in Figures 9 and 10. As such, after extended high-humidity conditioning, second-bond wedge lifts are more prevalent.

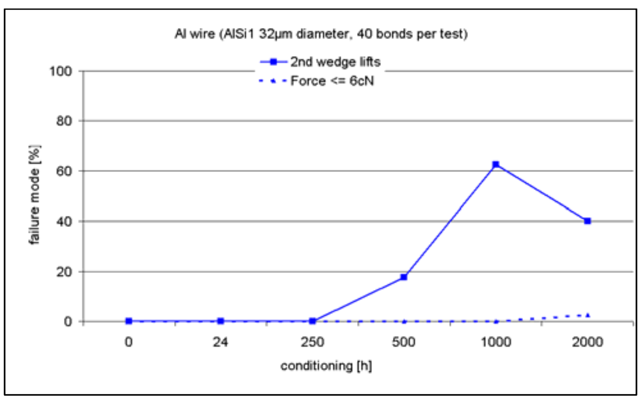


Fig. 13 Second-bond wedge lifts and average pull forces ≤ 6 cN for aluminum wire heat (85°C) and humidity (85%) conditioning

The second-bond wedge lifts were subsequently determined to have separated at the gold-palladium interface. SEM EDX analysis clearly showed a gold peak on the AlSi1 wire, whereas no gold was detected on the bonding surface. This would seem to indicate a possible adhesion/metallization issue (i.e. gold over palladium), which must be further investigated.

Figure14 provides a more detailed analysis of the pull forces associated with heel breaks and second-bond wedge lifts. Focusing solely on the average pull forces for heel breaks, it is apparent that the decrease in pull force over time is not as dramatic as that experienced in the dry-heat aging tests. The average pull force after 2000 hours of heat/humidity conditioning still remains 2-3 cN greater than that of the dry heat conditioned samples (See Fig. 9 and 10).

Despite the incidence of second-bond wedge lifts after 250 hours of heat/humidity conditioning, Figure 14 shows that the average pull force for second-bond wedge lifts after 2000 hours still maintained a value of slightly more than 10 cN. This result is comparable to the pull forces for the dry-heat and thermo-cycle conditioned aluminum wire samples, which apparently lost mechanical hardness and strength through diffusion reactions within the aluminum-silica matrix, as shown in Fig. 9 (at 250 hours), Fig. 10 (at 24 hours), Fig. 12 (at 1000 cycles).

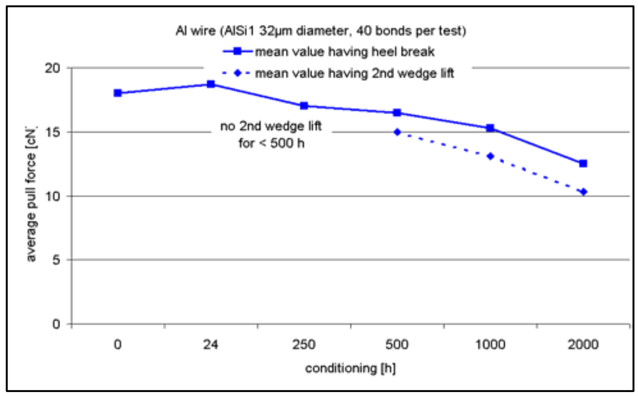


Fig. 14 Average pull forces for aluminum wire heel breaks and second-bond wedge lifts bonds following heat (85°C) and humidity (85%) conditioning

Neither optical stereo microscope nor SEM could clarify if any galvanic corrosion effect is involved, which would explain a reduced adhesion between the AlSi1 wire and the palladium surface. Therefore, several wire bonds were examined following 2000 hours of heat/humidity conditioning. None of the aluminum-palladium interfaces showed any indication of delamination. The palladium layers were not mechanically removed during bonding, nor were corrosion products or any delamination visible between wire and surface.

A galvanic corrosion effect could be contributing to the occurrence of second-bond wedge lifts and is well known in situations involving aluminum bonding to silver surfaces. If any galvanic corrosion effect is involved, degradation of AlSi1 wires on palladium surfaces occurs at a considerably slower rate than on silver. Testing after high humidity conditions for much longer than 2000 hours could provide more detailed information on this effect. For chip-on-board applications, the wire bridges would be encapsulated and therefore protected from the high humidity environment, which should significantly lessen the effect of any humidity-related reaction.

CONCLUSIONS

Based on the tests performed in this evaluation of the Ni/Pd/Au surface, the following conclusions are offered:

1. All gold-wire bond pull force testing exceeded the pass criteria after the 2000-hour high temperature aging at 125°C and 150 °C. The gold-wire bonds also passed the pull force testing after the heat/humidity conditioning (85°C and 85% RH), as well as the 2000 thermo-cycle conditioning (-40°C to 125°C).

Fig. 15 Image of gold ball bond on Ni/Pd/Au following 2000 hours heat conditioning (150°C)

2. The results from the gold wire bonding investigations (Figures 3-6) show that the overall pull force did not decrease over time, regardless of high-temperature aging or high-humidity or thermo-cycling conditioning. In all cases, the bond strength after reaching the maximum level of each conditioning is comparable to the "as-is" bonds.

3. Even after 2000 hours of dry-heat or humidity conditioning or 2000 thermo-cycles, none of the gold wire bonds (1) showed any evidence of wedge lifts, (2) had pull forces of less than 6 cN, or (3) showed a decrease in mean pull force values. Neither temperature, humidity, nor thermal cycling resulted in a decrease in mechanical properties of the bond wires or the bonds to the Ni/Pd/Au.

4. For aluminum wire bonds, the average pull forces were only marginally below the established pass criteria of 10.5-12.0 cN following 2000 hours of dry heat conditioning (125°C and 150°C) and 2000 thermo cycles (-40°C to 125°C). A minimum average pull force of nearly 10 cN was maintained.

5. None of the aluminum wire bonds showed any evidence of wedge lifts following either dry-heat conditioning (125°C and 150°C) or thermo-cycle conditioning (-40°C to 125°C). In addition, the average pull force exceeded the minimum test criteria of 6 cN in all tests.

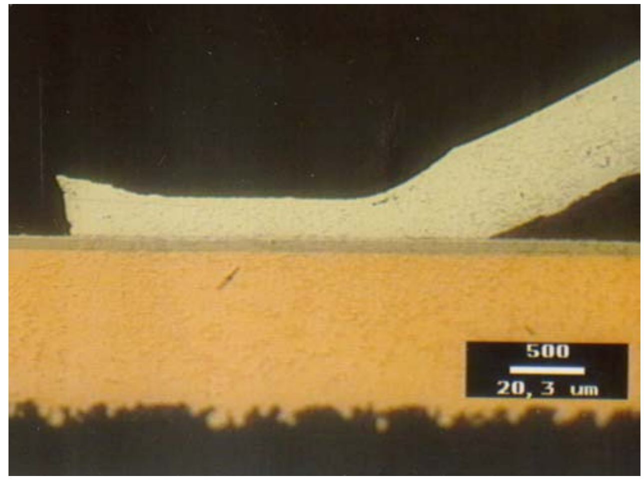


Fig. 16 Image of aluminum wedge bond on Ni/Pd/Au following 2000 hours heat conditioning (150°C)

6. Following 500 hours of heat and humidity conditioning (85°C and 85% RH) of the aluminum wire bonds, second-bond wedge lifts occurred. Pull forces associated with the wedge lifts still averaged above 10 cN throughout the test. Additional investigations are required to determine the specific cause of the wedge lifts.

7. Throughout the testing of aluminum wire bonding, the temperature-related effect of silica diffusion and concentration in the wire resulted in decreased pull forces. The impact of this influence varied depending on the type of sample conditioning.

The Ni/Pd/Au process represents a cost-effective alternative to the more conventional use of silver, silver/palladium and gold pastes as bondable surfaces on ceramic materials in the manufacture of electronic devices. The results of this examination further support the use of the Ni/Pd/Au process as a gold- and aluminum-wire bondable finish for ceramic materials.

REFERENCES:

1. Dr. Halser, Bohn; Dr. Krause; Dr Nowottnick; Pape, Schulz; "Shear Test of BGA-Solder Balls", Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (IZM) Abteilung "Baugruppentechnologie und Verbindungstechniken"; Atotech Deutschland GmbH, Berlin, March 1998

2. Dr.Ing. M. Schneider-Ramelow, Dr.Ing. K.D. Lang, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration IZM-Berlin; Dr.Ing F. Rudolf, Dr.Ing. I. Witte, TU Dresden Fakultät Elektrotechnik und Informationstechnik, Institut für Halbleiter- und Mikrosystemtechnik und Institut für Feinwerktechnik; Dr.Ing. D. Metzger, Atotech, "Chip on Board (COB) –Technik in hermetisch gekapselten

Mikrosystemen für den Einsatz im rauhen und feuchten Umfeld der Meeresbiologie", Atotech, Berlin, March 2003

3. R. Wayne Johnson, M. Palmer, M. J. Bozack and T. Isaac-Smith, "Thermosonic Gold Wire Bonding to Laminate Substrates with Palladium Surface Finishes," IEEE Transactions on Electronics Packaging Manufacturing 22 (1999) 7

4. J. Li, M. J. Bozack, R. H. Zee, "Direct Evidence of Segregation of Carbon at Rhenium Surfaces," J. Mat Sci. 34 (1998) 239