Mechanical and Corrosion Properties of Aluminum Wires for Ultrasonic Bonding

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Abstract

Aluminum fine wires for ultrasonic bonding in integrated circuit packages, discrete components and power devices were studied. The mechanical and corrosion properties of Al-1%Si, Al-Mg (Al-0.5%Mg and Al-1%Mg), specialty alloys (Al-Mg-Pd, Al-Cu-Fe), and alternative aluminum materials were characterized and compared. The wires were drawn to final sizes and annealed at various temperatures. Break strength, yield strength, and elongation were measured at each condition for each material. Corrosion properties were characterized via surface and cross-section examination, together with residual strength after pressure cooker tests. The results permitted wire types to be ranked according to their tensile and corrosion properties. In addition, a corrosion resistant aluminum for heavy wirebonding application was introduced.

Key words:

Aluminum Wire, Ultrasonic Bonding, Mechanical Properties, Pressure Cooker Test, and Corrosion Resistance.

1. Introduction

Aluminum fine wires have been used in ultrasonic bonding for integrated circuit packages, discrete components and power devices for many years. The wire production processes involve drawing, or less frequently extrusion, to final sizes of 20µm to 0.50mm, and thermo-mechanical treatments in the intermediate and final process steps to achieve desired mechanical properties. Alloying elements are added to the aluminum matrix to increase material strength and corrosion resistance.

Most studies on aluminum fine wires have concerned Al-1%Si and Al-Mg alloys [1-11, 17]. The tensile properties of wires can significantly affect their applications and the bonding parameters. The desired mechanical properties are obtained by an anneal or a stress-relief at final wire diameter. During subsequent assembly and stress testing of the package, the aluminum wires will in some applications experience much higher temperature than the final wire annealing temperatures. Therefore, the mechanical properties of the wire will change. Corrosion of wires due to moisture penetration can cause serious wire degradation and, in some cases, electrical open circuits.

In this study, the mechanical and corrosion properties of aluminum wire products, such as Al-1%Si, Al-Mg (Al-0.5%Mg and Al-1%Mg) , specialty alloys (Al-0.5%Mg-0.1%Pd, Al-0.7%Cu-0.7%Fe), and alternative aluminum materials, were characterized and compared in detail. The wires were drawn to final size and annealed at various temperatures. Break strength, yield strength, and elongation were measured at each condition for each material. Corrosion properties were characterized via surface and cross-section examination, together with residual strength after pressure cooker tests (PCTs). Wire types were ranked according to the tensile strength and corrosion properties, and a corrosion resistant aluminum material for heavy wirebonding application was introduced.

2. Materials And Experiments

A total of eight aluminum and aluminum alloys were investigated in this study. The materials were Al-1%Si, Al-0.5%Mg, Al-1%Mg, Al-0.5%Mg-0.1%Pd, Al-0.7%Cu-0.7%Fe, a 99.99% commercial aluminum (AL1199), a 99.99% aluminum corrosion resistant alloy (AL4NCR) and a 99.999% aluminum (AL5NPS). All materials have FCC crystal structure and are solution strengthened, except for Al-1%Si and Al-0.7%Cu-0.7%Fe, which are precipitation strengthened. The materials in this study were taken from the production line of American Fine Wire of Kulicke and Soffa Industries, Inc.

The materials were cast and homogenized to obtain uniform microstructure and distribution of strengthening elements. Ingots were swaged or extruded to produce rods of 5mm (0.20”) diameter, followed by drawing to the final diameter of 76µm (0.003”). Depending on material type, different intermediate thermo-mechanical processes were applied to obtain desired mechanical properties and microstructure for each wire.

At final size, all wires were wound on spools and annealed at various temperatures, ranging from 100°C to 400°C, for 30 minutes. Tensile tests were conducted on a Micro-Instron machine for wire at each heat condition, following ASTM F219. In all tensile experiments, the gauge length of the wire was 254mm (10 inches) and the rate of traverse was 25.4mm/min (1 inch/min). A typical tensile curve [1] is shown in Figure 1. The break strength and elongation are determined directly from the tensile curves, and the yield strength is defined as the 0.2% offset strength. Five duplicated tests were performed for each sample and the average was used for subsequent analyses.

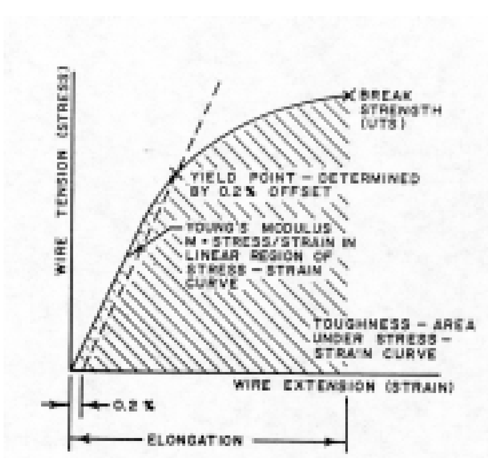

Figure 1. A typical tensile curve of 76µm wire at room temperature[1] .

PCTs of wires at 76µm diameter were conducted at 121°C and 2 atmospheres for 24 hours and 48 hours. All wires for PCTs were previously annealed at 150°C for 30 minutes in air. After PCTs, the wire surfaces were examined via SEM and also metallographically by means of longitudinal cross section. In addition, tensile tests after PCTs were performed for selected wire types to examine the residual tensile strength.

3. Mechanical Properties

3.1. Experimental Results

The changes in average break strength, yield strength, and elongation with annealing temperatures for each material are shown in Figures 2 through 4. Break and yield strengths follow the same general trends with the increase in annealing temperature. As seen from Figure 2, annealing at 100°C has little affect on the initial break strength. Above 100°C break strength decreases significantly with increase in annealing temperature. Note, however, that for Al-0.5%Mg, Al-Cu-Fe and AL5NPS, the break strengths remain substantially constant above temperatures of 300°C, 250°C, and 200°C, respectively, with little further loss of strength. The yield strength for all materials decreases progressively in the range 100°C to 300°C, then remains essentially constant up to 400°C. Based on wire strength the materials can be ranked, thus; (1) Al-0.5%Mg has the highest break strength among all materials at lower and intermediate annealing temperatures, 125°C~300°C. (2) Al-1%Si and Al-1%Mg have essentially the same break and yield strengths over the entire annealing temperature range. (3) For specialty alloys Al-Mg-Pd and Al-Cu-Fe, the break strength of Al-Mg-Pd drops continuously in the entire annealing temperature range. The break strength of Al-Cu-Fe drops rapidly from annealing temperature 100°C, and then remains constant at 200°C. (4) AL1199 and AL4NCR are both 99.99% aluminum materials with comparable tensile strengths. AL4NCR provides an alternative material to AL1199 for ultrasonic bonding in power devices. (5) AL5NPS is the purest aluminum material, and has the lowest tensile strength of all the materials.

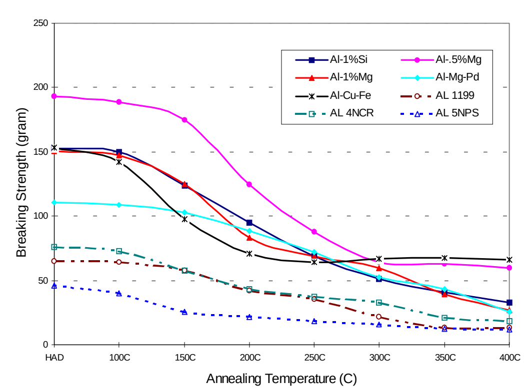

Figure 2. Breaking strength of 76µm diameter wires annealed at various temperatures.

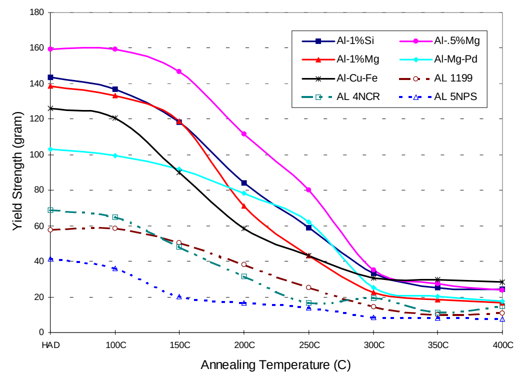

Figure 3. Yield strength of 76µm diameter wires annealed at various temperatures.

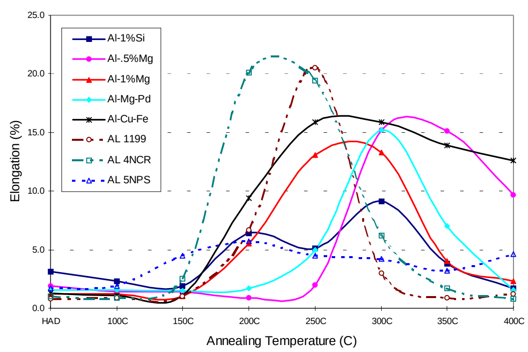

Figure 4. Elongation of 76µm diameter wires annealed at various temperatures.

Wire elongation depends on both material type and heat treatment. Except for Al-1%Si, three stages could be identified for all materials, depending upon the annealing temperature. Below 150°C wire elongation changed only slightly, with exception of AL5NPS (99.999% Al), which showed a little increase. For the other materials, wire elongation increased with annealing temperature, reaching maximums after the wires had been fully recrystallized with little accompanying grain growth. It then decreased as annealing temperatures rose further, and grain structures coarsened. The two 99.99% and one 99.999% aluminum wires reach their maximum elongations between 200°C and 250°C. The aluminum alloy wires, however, reached maximum elongations between about 275°C and 325°C. The elongation curve of Al-1%Si displays two peaks, the first at 200°C, which is followed by a decline to a low at 250°C. Subsequently, a second, and higher peak is reached which at about 300°C. All wires decreased in elongation when annealed above those corresponding to their maximum elongations.

3.2. Discussion

Strength and elongation depend on material composition, thermo-mechanical conditioning and deformation history. The strength of Al-0.5%Mg is higher than that of Al-1%Mg throughout the entire annealing range, as shown in Figure 2. This fact can be attributed to the thermo-mechanical history prior to the final anneal at final size, that is, Al-0.5%Mg had more prior plastic deformation than Al-1%Mg. A similar phenomenon was also found for Al-1%Si wires of 32µm diameter with different prior deformation histories[2,3], when annealed in the temperature range 100°C~500°C. In general, work hardening is the dominant strengthening mechanism in fine aluminum wire manufacturing.

The elongation of Al-1%Si, as seen from Figure 4, falls to a minimum when annealed at 250°C. Similar phenomena were reported elsewhere [2-5] in the temperature range 250°C~300°C for 32µm (0.00125") diameter wires. Jones et al. [5] attributed the elongation reduction to the rotation of drawing texture axis. They suggested that the axis change from orientation <110> in the as-drawn condition to <111> in the recrystallized condition caused the elongation reduction. An alternative mechanism, competition between grain structure change and silicon precipitation and coarsening at the grain boundaries and in the matrix, may also explain this phenomenon. The wire grain structure experiences recovery, recrystallization, and grain growth as annealing temperature increases. At the same time, silicon tends to reprecipitate and coarsen at the grain boundaries and in the matrix since its solubility [12] in aluminum is about 0.16% at room temperature versus 0.25% at 400°C. The probability for silicon to precipitate and coarsen will increase as the annealing temperature rises. It is postulated that this phenomenon has an embrittling effect. Below 200°C, recovery and recrystallization predominate, and ductility and elongation increase as temperature increases. In the range 200°C~250°C, silicon precipitation and coarsening predominates, and causes elongation reduction. In the range 250°C~300°C, recrystallization and moderate grain growth predominate again and elongation increases. Above 300°C, both silicon precipitation and coarsening, and excessive grain growth induce elongation reduction.

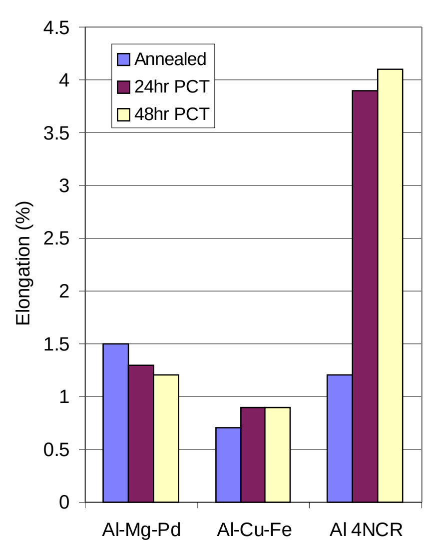

Figure 5a. Breaking strength.

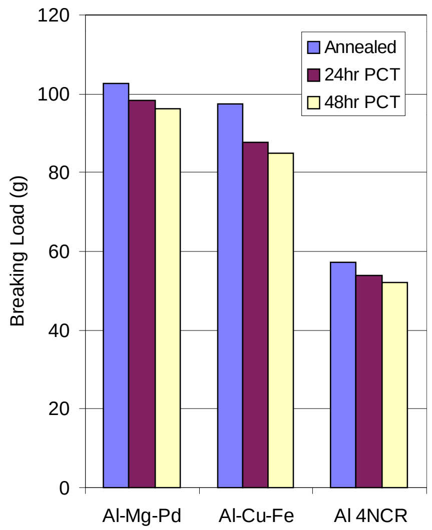

Figure 5b. Elongation of 76µm diameter wires before and after pressure cooking tests.

4. Corrosion Properties

4.1. Experimental Results

SEM and optical images of wires surfaces and cross sections after 24 hours PCT are shown in Figures 6 through 13 for materials in this study. SEM and optical images of wire surfaces and cross sections for Al-1%Si and AL4NCR after 48 hours PCT are also shown in Figures 6 and 11.

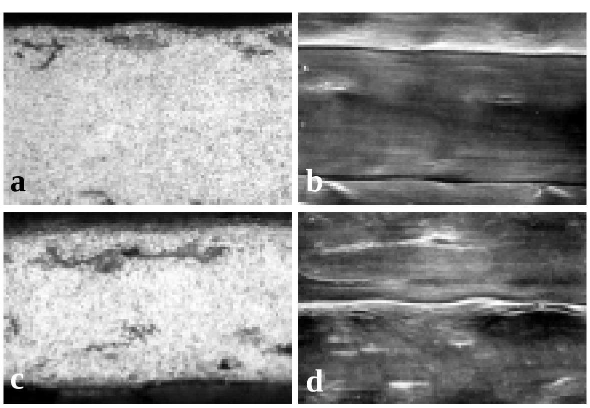

Figure 6. Al-1%Si wire after pressure cooker tests, 500X. (a) OM image, 24 hours; (b) SEM image, 24 hours; (c) OM image, 48 hours; (d) SEM image, 48 hours.

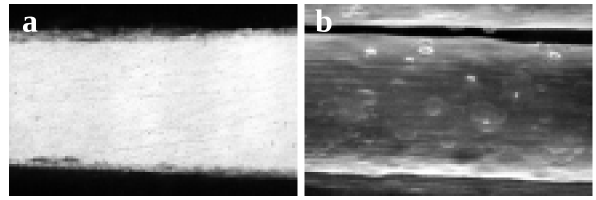

Figure 7. Al-0.5%Mg wire after pressure cooker test for 24 hours, 500X. (a) OM image, (b) SEM image.

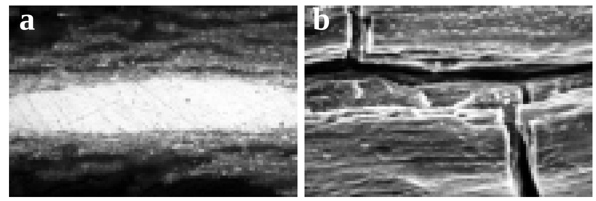

Figure 8. Al-1%Mg wire after pressure cooker test for 24 hours, 500X. (a) OM image, (b) SEM image.

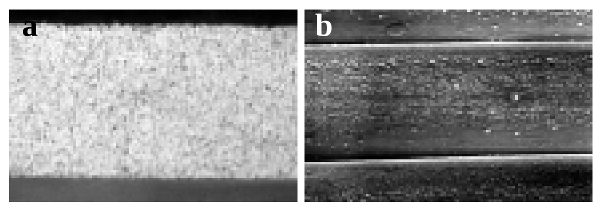

Figure 9. Al-0.5%Mg-0.1%Pd wire after pressure cooker test for 24 hours, 500X. (a) OM image, (b) SEM image.

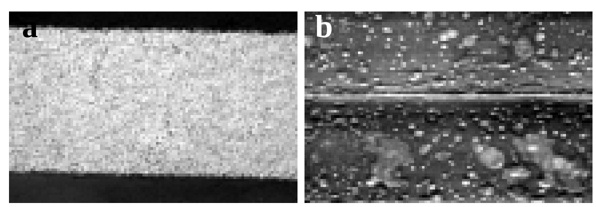

Figure 10. Al-0.7%Cu-0.7%Fe wire after pressure cooker test for 24 hours, 500X. (a) OM image, (b) SEM image.

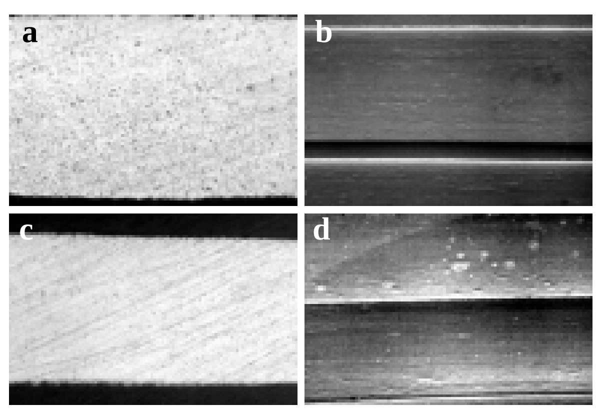

Figure 11. Al 4NCR wire after pressure cooker tests, 500X. (a) OM image, 24 hours; (b) SEM image, 24 hours; (c) OM image, 48 hours; (d) SEM image, 48 hours.

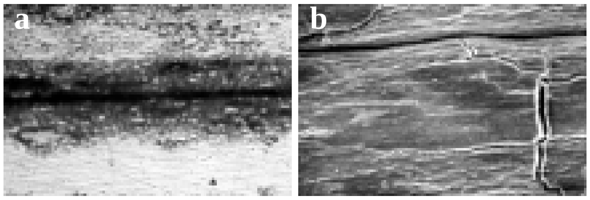

Figure 12. Al 4N (1199) wire after pressure cooker test for 24 hours, 500X. (a) OM image; (b) SEM image.

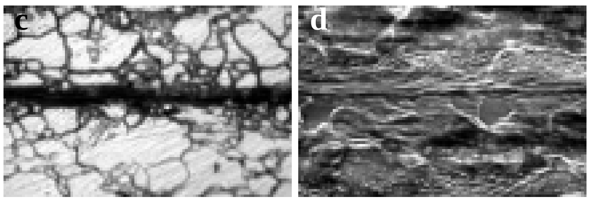

Figure 13. Al 5NPS wire after pressure cooker test for 24 hours, 500X. (a) OM image; (b) SEM image.

As seen from Figures 6 through 13, when significant corrosion occurred, it was predominantly intergranular corrosion. The amount of corrosion varied greatly depending on wire composition. Based on the severity of corrosion, the materials can be divided into three groups: (1) slightly corroded, (2) severely corroded, and (3) catastrophically corroded.

Three materials, Al-Mg-Pd, Al-Cu-Fe, and AL4NCR, fall into the slightly corroded category, as seen from Figures 9, 10, and 11. These wires displayed only superficial surface corrosion. The wires were mechanically and electrically functional. The tensile tests were performed after PCTs for 24 and 48 hours. The residual break strength is shown in Figure 5a, and the elongation before and after PCT is shown in Figure 5b. The break strengths of all three wires decreased after PCT. Al-Cu-Fe corroded more than the other two materials, as seen from the SEM and optical pictures, as well as from Figure 5a. The elongation, on the other hand, showed little change for the two alloys, but increased for the pure aluminum as PCT time increased.

Two materials, Al-1%Si and Al-0.5%Mg, displayed severe intergranular corrosion. As seen from Figures 6 and 7, the corrosion penetrated 20-50% of the wire cross section. This degree of corrosion is considered functionally unacceptable.

Three materials, Al-1%Mg, AL1199 and AL5NPS, suffered complete corrosion with catastrophic intergranular corrosion and fracture completely through the wires, as seen from surface SEM and OM cross-section images, Figures 8, 12, and 13. Contrary to some published data [18, 19], neither 99.99% or 99.999% aluminum is necessarily corrosion resistant.

4.2. Discussion

In a high pressure steam environment, some aluminum and aluminum alloys exhibit intergranular corrosion behavior. Intergranular corrosion is the selective attack of the grain boundary zone, with no appreciable attack of the grain matrix. The mechanism is an electrochemical reaction. An anode and a cathode of the local microelectric circuit are formed due to electrical potentials between the second-phase microconstituents at grain boundaries and the depleted aluminum solid solution from which the constituents formed [18, 19].

Pd addition to an aluminum matrix was found to improve corrosion resistance in moist environments. The corrosion protection mechanism in the Al-Pd alloy is explained in terms of the strengthening of the surface protection film by the addition of Palladium. The protective film makes the moisture penetration into grain boundary more difficult[16]. The addition of Mg to an aluminum matrix was found to improve wire bondability and corrosion resistant if the Mg composition is small [16]. Some other transition metals, such as Fe, Cu, In, Ni and their combinations, can also provide effective corrosion resistance [14, 18-19].

Aluminum has long been considered resistant to galvanic corrosion in moist environments [18-19]. However, this finding is not always true, depending on the trace and doping elements present in the nominally pure aluminum. The function of each element in the aluminum material needs to be further investigated.

The situation of aluminum wires in plastic encapsulated packages is more complicated. Corrosion of the wires will be affected by; (1) The rate of permeation of moisture in the package, which is partly of a function of package design and specific molding compound, and (2) The concentration of water-extractable ions in the molding plastic and their species, for example, chlorine and bromine. This work has not been done yet, and is a topic for future study.

5. Summary

The mechanical and corrosion properties of aluminum ultrasonic bonding wires were evaluated in this study. Wires of 76µm (0.003”) diameter were annealed at various temperatures and tensile tested. Pressure cooker tests were used to define the corrosion resistance of each material. It was found that:

1. The aluminum materials could be ranked in five levels of break and yield strengths. These are: (1) Al-0.5%Mg, (2) Al-1%Si and Al-1%Mg, (3) specialty alloys of Al-Mg-Pd and Al-Cu-Fe, (4) 99.99% aluminum, and (5) 99.999% aluminum.
2. Strength and elongation depend on material composition, thermo-mechanical processing, and deformation history. Due to prior thermo-mechanical history, the Al-0.5%Mg material had higher strength than Al-1%Mg material.
3. The materials experience recovery, recrystallization, and grain over growth in the temperature range examined. With exception of Al-1%Si, the elongation for all materials increases to a peak and then declines as annealing temperature increases The mechanisms by which the elongation curve for Al-1%Si displays two peaks are also discussed.
4. Corrosion resistance of aluminum wire materials, defined by pressure cooker test, was evaluated and compared. The materials can be divided into three groups based on severity of corrosion. They are: (1) Slightly corroded materials which in-

clude Al-Mg-Pd, Al-Cu-Fe and AL4NCR, (2) Severely corroded materials which include Al-1%Si and Al-0.5%Mg, and (3) Catastrophically corroded materials which included Al-1%Mg, AL1199 and AL5NPS. Control of trace elements and alloying additions can significantly increase corrosion resistance.

5. A new 99.99% aluminum material (AL4NCR) was introduced to provide better corrosion resistance than the commercial aluminum (AL1199). These two materials have comparable tensile mechanical properties.

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About the authors

Hongwei Liu is currently a Senior Packaging Engineer at Tessera in San Jose, California. This work was performed at American Fine Wire Corporation while he was working as a metallurgist in Alabama. His experiences cover both Mechanical Engineering and Material Science aspects of microelectronics packaging developments and manufacturing. Dr. Liu received his Doctorate Degree in Applied Mechanics from Lehigh University in Pennsylvania in 1996, and his Master and Bachelor Degrees in Mechanical Engineering from Tsinghua University in Beijing in 1987, and 1984, respectively. Dr. Liu is a member of IMAPS.

Nathan Fank received a Bachelor of Science Degree in Chemistry from Huntingdon College in 1991. He joined American Fine Wire as a process engineer in 1992. Mr. Fank is currently the Product Marketing Manager for aluminum bonding wire.

Caroline Acosta received a Bachelor of Science Degree in Materials Engineering from Auburn University in 1995. She joined American Fine Wire in 1996 where she worked with the manufacturing process and product development of gold and aluminum bonding wire.

Recommended reading G.G. Harman, Wire Bonding in Microelectronics : Materials, Processes, Reliability, and Yield, 2nd edition, McGraw-Hill Electronic Packaging and Interconnection Series, 1997. G.G. Harman, Reliability and Yield Problems of Wire Bonding in Microelectronics, 1991, ISHM, Reston.Â K. V. Ravi, and E. Philosky, "The Structure and Mechanical Properties of Fine Diameter Alumina-1% Si Wire," Metallurgical Transactions, 2, March 1971, pp. 712-717.Â V. A. Pitt, C. R. S. Needes, and R. W. Johnson, "Ultrasonic Aluminum Wire Bonding to Copper Conductors," Electronics Components Conference, 1981, pp. 18-23.Â S. Thomas, and H. M. Berg, "Micro-Corrosion of Al-Cu Bonding Pads," 23d Annu. Proc. Wire Bonding in Microelectronics About the Author George G. Harman is a retired Fellow of the National Institute of Standards and Technology (NIST). He has a BS in industrial physics from Virginia Polytechnic Institute & State University and an MS in physics from the University of Maryland (1959).Â Ultrasonic Bonding Systems and Technologies, Including a Description of the Ultrasonic Wire Bonding Mechanism . 2.1 Introduction . . .Â Typically, they were cited as â€œpurple plague,â€ underbonding, overbonding, and nonspecified contamination-induced corrosion. Currently (2009), dozens of chemical, metallurgical, and mechanical failure mechanisms have been identified.