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Wire-to-wire bonding of μm-diameter aluminum wires for the Electric Solar Wind Sail

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ABSTRACT

We present a novel ultrasonic wire-to-wire bonding method for bonding two micrometer-thick metal wires together. A special jig and an industrial wire bonder perform the bonding. This wire-to-wire bonding is the core unit process to produce space tether for the Electric Solar Wind Sail. The proposed method was validated experimentally with 38 bonds where a 25 μm and a 50 μm by diameter Al wires that were first bonded together after which the bond was pull tested. The measured average pull force was (74 ± 15) mN whereas the lowest pull force value was 40 mN. The results show that wire-to-wire bonds of sufficient strength can be produced for the Electric Solar Wind Sail tether application. Tether manufacturing was demonstrated with a separate test where a 1.4 m long tether was produced featuring more than 100 wire-to-wire bonds.

1. Introduction

The Electric Solar Wind Sail (E-sail) exploits dynamic pressure generated by the solar wind to produce thrust for the spacecraft [1]. A system can be designed that provides 1 N of thrust that could be produced continuously over a period of years by a 100 kg mass E-sail featuring 2000 km of tether [2]. This performance is orders of magnitude higher than what other current or planned space propulsion systems produce.

The key technical parts of the E-sail are its long, thin, conducting, micrometeoroid-resistant tethers. For micrometeoroid-resistivity a multiline tether is needed [3]. One promising way to produce the multiline tethers appears to be to use ordinary microelectronics metal wires bonded by a wire-to-wire technique. For full-scale production, 100 tethers, 20 km long, need to be produced by using 20–50 μm thick metal wires. However, for the first planned space mission to measure the E-sail effect, only one 10 m long tether is needed. This requires 2000 bonds to be performed reliably.

The specifications for each wire-to-wire bond in the E-sail tether are estimated based on theoretical calculations and simulations [2]. The most important qualification parameter is the pull force of the single wire-to-wire bond, which should exceed 50 mN if 25 μm thick wires are used. This design produces 1 N thrust for the proposed E-sail.

The conductivity, density, and tensile strength of common 25 and 50 μm thick wires made of Al(1%Si) alloys meet the requirements of the E-sail project. The work reported herein therefore focuses on showing that the necessary bonds can be produced relying on existing ultrasonic bonding techniques performed with an industrial wire bonder.

Wire bonding is a widely used technique to produce an electrical and mechanical bond between a thin metal wire and a metal pad. Trillions of wire bonds are produced annually in microelectronics production [4]. Production speeds are high, and the yields of wire bonding process approach 100% [5]. Typically microelectronic wire bonding is done to a flat substrate, such as a printed circuit board or a silicon chip. To our knowledge ultrasonic wire-to-wire bonding of μm-scale metal wires has not been done before.

2. Wire-to-wire bonding

The bond pad and the wire are about equally hard in classical wire bonding [4]. We chose to use a 50 μm-by-diameter medium hardness wire Al(1%Si) as the base wire onto which a 25 μm-by-diameter soft wire Al(1%Si) was bonded. The 50 μm wire with a breaking load of 600–660 mN was manufactured by Tanaka Electronics, whereas the 25 μm wire, with a 130–150 mN breaking load, was manufactured by Kulicke & Soffa. This wire combination

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was chosen to maximize the breaking strength of the wire bond and the wire itself.

The 60 kHz automatic wire bonder Delvotec 6400 used for the wire-to-wire bonding process was equipped with a standard wedge, Gaiser Tool 2130-2525-1.0.

Due to the wire deformation during the bonding process and the small diameter of the wires to be bonded together, wire-to-wire bonding was performed with the wires running parallel to each other (Fig. 1).

The jig was designed to provide, with minimum base wire deformation, a firm support for the base wire and to allow easy bond removal after completing the wire-to-wire bonding process. The key requirement in the jig design was to restrict the wire displacement during the ultrasonic bonding process. Typically the bonding substrate (PCB-board, chip, package) is firmly attached to the work holder to avoid any displacement of the bond pad on the substrate while allowing relative displacement, stick–slip motion, between the bond wire and the bond pad.

The jig supports the base wire by means of a substrate featuring a rectangular-shaped groove that runs parallel to the wire axis Fig. 1. The groove guides the base wire to the bonding position and restricts the lateral displacement of the base wire.

The base wire displacement along the wire is restricted by the friction caused by the groove, and by the constant tension produced by the clamps. The groove width is close to the wire diameter whereas it is half a wire diameter deep Fig. 1.

Since existing bonding equipment and tools are designed for bonding to flat pads, the base wire should present a flat surface in the bonding area. The base wire was therefore flattened by indenting it with a 1.5 mm-diameter metal cylinder after positioning the wire in the groove (Fig. 1). This approach was chosen to avoid any sharp edges between the cylindrical and flat part of the indented base wire.

The jig also accommodates the PCB with Au pads for a second bond of the 25 μm wire. This jig feature serves pull test purposes.

After positioning the base wire and fixing its ends to the jig, 100–200 mN of tensile force was applied to the wire. The additional load of 10–20 mN, generated by the clamps pressing on the base wire, fixed it firmly in the groove. Flattening the wire to prepare a bondable area was done by pressing the metal cylinder with a 2 N load orthogonally against the wire. This produces into the base wire a pseudo flat oval-shaped surface, 200 μm long and 40 μm wide. Bonding the 25 μm Al wire loop was done using the Delvotec 6400. The following main bonding parameters were employed: US Time – 100 ms; US Power – 30 (Machine units); Bond Force – 0.3 N.

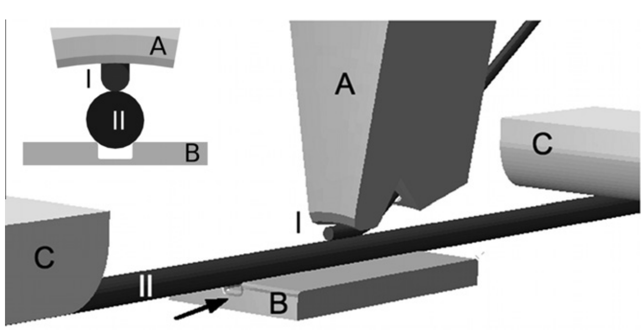

Fig. 1. The wire-to-wire bonding process. The base wire (II) is attached to the grooved substrate (B) with clamps (C). The tension created by the clamps together with the support from the groove (arrow) in the substrate keeps the base wire firmly in it's position during the bonding process. The standard bonding wedge (A) bonds the upper wire (I) to the base wire. The insert (top left) shows the front view of the bond location.

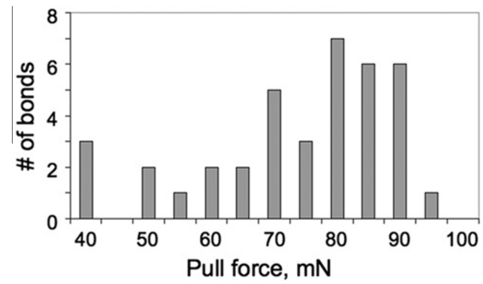

Fig. 2. Measured pull forces for 38 wire-to-wire bonds.

Each bond was inspected visually under an optical stereo zoom microscope, a Carton NSZ-70, employing 20–70× magnification. Bond location on the base wire, bond color, and bond shape were checked to find anomalous bonds. Good bond criteria: (a) silver color, oval shaped bond spot, (b) bond spot width 1.5–2.0 times larger than the initial wire diameter, (c) no cracks or ruptures neither on the bond spot nor on the neck of the bonded wire, (d) bond deformation 10–15 μm (40–60% of bond diameter) and, (e) small or invisible deformation of the base wire.

A manual pull test was done with a Correx Gram Force Gauge (2–15 g). The angle between the base and upper wires during the pull test was ~30°. The maximum sustainable pull force of the base wire after pull testing the upper wire was also measured.

A Hitachi 4800 Scanning Electron Microscope was used to image the bonds. The bonded wires were removed from the jig and carefully set onto a piece of conductive tape while avoiding to mechanically disturb the bond. Bonds to be imaged were produced with the same bonding parameters as those used in the test. These bonds were not pull tested.

The validation test, to show the capability to produce the tether with the proposed wire-to-wire bonding technique was done employing the semiautomatic K&S wedge bonder and a custom made jig.

3. Results

The capability of the proposed method to produce wire-to-wire bonds was confirmed with 38 measurements (Fig. 2). The measured average pull force was 74 ± 15 mN (one standard deviation). These measured pull forces are less than typical bond pull forces achieved in high quality industrial production (>90 mN), as expected, since the base wire compared to the typical bond pad is less satisfactory for the bonding. The breaking force for base wires after bonding exceeded 0.4 N.

Visual bond inspection showed that most bonds (35/38) fulfilled the 'good bond criteria'. For three bonds we measured only

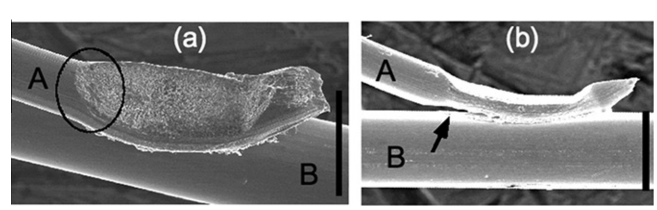

Fig. 3. SEM images of two wire-to-wire bonds. A 25 μm wire (A) is bonded to the 50 μm base wire (B). (a) The bond shape is visible. No cracks in the encircled neck area. (b) The unbonded area under the neck is shown with an arrow. The black size bar is 50 μm.

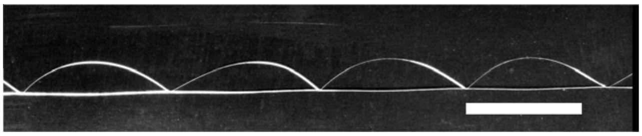

Fig. 4. Multiline 2-wire tether produced using wire-to-wire bonds. The loop height is 2.5 mm and the loop length is 12 mm. White scale bar is 10 mm long.

40 mN pull force. These bonds were slightly misaligned during the bonding process and not bonded to the center of the base wire.

Two wire-to-wire bonds are shown in Fig. 3. The shape of the bonds and the deformation ratio are good. No cracks are visible on the neck of the bonds. However, the unbonded area visible in the bonded interface may limit the bond strength.

In the validation test several tethers were manufactured to prove that the wire-to-wire bonding technique can be used for E-sail tether production. The longest tether manufactured so far is 1.4 m long featuring more than 100 bonds (Fig. 4).

4. Conclusions

The wire-to-wire bonding technique was introduced and the results of the validation measurements were shown. Wire-to-wire bonds can be produced with acceptable quality to build the Electric Solar Wind Sail. The average pull force for the wire-to-wire bonds with 50 μm base wire and 25 μm wire was 74 ± 15 mN. The capacity of the wire-to-wire bonding technique to produce tethers for the E-sail application was validated by producing a 1.4 m long tether including more than 100 wire-to-wire bonds.

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