Investigating the Copper Peel and Solder Joint Shear Strength on Biodegradable Substrates

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Abstract—The amount of electronics waste is increasing rapidly, and replacing traditional electronics materials with biodegradable alternatives is essential where possible. Four types of biodegradable substrates with 35 μm thick laminated copper layer have been analysed in this research work. All the substrates are based on polylactic acid laminates with flax reinforcement. The first type is a pure PLA laminate. The second, third and fourth types incorporate polymer interlayers (polypropylene or polyamide) to facilitate the adhesion between the copper layer and the substrate. Note that the interlayers are not biodegradable but will be swapped with biodegradable alternatives in the future. Copper peel strength was measured using a standard test pattern described in IPC-TM650. The copper layers were peeled off using an Instron 5965 test equipment, and the applied load was recorded automatically. A custom sliding sample holder was designed, allowing the vertical peeling of the copper layer. In addition to the copper peeling test, surface-mounted resistors in different sizes were assembled with low-temperature reflow soldering, and the shear strength of their solder joints was investigated.

Keywords— polylactic acid, biodegradable substrates, copper layer adhesion, peel strength, wettability

I. Introduction

Nowadays, the amount of electronic waste is increasing year by year, with 57 million tonnes worldwide in 2021 and nearly 138 thousand tonnes in Hungary in 2020. The problem of electronic waste has received increasing attention in recent years, even at the European policy level, leading to the European Green Deal [1]. For example, The Joint Research Centre of the European Commission established a competence framework on European sustainability, called GreenComp, as an exemplary action within the Green Deal.

On the research level, investigations started about biodegradable electronic substrates. However, the thermal and mechanical properties of early-stage substrates were below those of FR4 (Flame resistant, Class 4) substrates. In initial experiments, banana stems and wheat gluten were tested [2], evaluating mechanical and thermal performance and resistance to humidity absorption. They found that reinforcements in biodegradable substrates (too) are inevitable in acquiring acceptable mechanical strength. Still, the strength is around 1/6th – 1/5th of the FR4 strength. The FR4 materials have a standard tensile strength higher than 310 MPa, while the biodegradable substrates reached 50–60 MPa. Flame retardancy (tested based on the UL-94 standard test method) of biodegradable substrates also lacks those of FR4 materials. Biodegradable substrates reached the V-1 classification compared to the classification V-0 of FR4 substrates. Treating biodegradable substrates with chemicals to increase flame retardancy is suggested by the authors Guna et al. [2]. However, it is also important to keep the environmentally friendly aspect of the substrates after flame retarding.

Acrylated Epoxidized Soybean Oil (AESO) resins + Chicken Feather Fibers (CFF) composites were also tested [3]. These composites provided much better strength (their flexural strength reached 100 MPa) and flame retardancy (V-0). On the downside, the copper adhesion to these substrates was relatively weak – the copper peel strength was as low as 0.6 N/mm (compared to the peel strength of FR4 substrates being above 1.4 N/mm).

Polylactic acid (PLA) has been increasingly popular in recent experiments. PLA has the advantage that the energy used in its production is 20-50% of that used in producing petroleum-based plastics. PLA is a fully biodegradable material, which can be reduced to lactic acid in an environment with the right temperature and humidity, and the lactic acid can be broken down into carbon dioxide and water by bacteria. The studies have mainly focused on the electrical properties of printed electronics on PLA. Mattana et al. demonstrated the feasibility of forming organic electronic devices on PLA [4], whereas Hwang et al. prepared hydration sensors on PLGA (poly lactic-co-glycolic acid) substrates [5]. However, other research works have shown the adhesion of the copper layer on this substrate type is still problematic in terms of mechanical properties [6]. The copper peel strength turned to be still about 0.6 N/mm, which needs improvementto prepare acceptable quality and proper reliability in terms of electronics circuits. Another issue is the low *Tg* (glass transition temperature) of PLA-based substrates (around 60°-100°C); therefore, connecting electrical components to these substrates is feasible only by using low-temperature solder alloys (like SnBi) or conductive adhesives as an alternative.

Continuing existing works on this topic, our research aimed to investigate PLA-based PLA/Flax composite-based biodegradable substrate. In these substrates, the mechanical properties are enhanced with flax reinforcement, and polymer interlayers promote copper layer adhesion.

II. MATERIAL AND METHODS

In this experiment, PLA/Flax biodegradable substrates were investigated from two aspects that are the most critical from the assembly point of view. The copper adhesion was measured using a standardised copper peeling test, and the mechanical strength of solder joints was assessed by soldering surface-mounted resistors onto biodegradable substrates.

A. *Investigated substrates*

Four types of biodegradable substrates have been analysed, which were different variations of the same core material. All of them are based on polylactic acid (PLA) laminates with flax reinforcement and impregnated with flame retardancy chemicals (FR-PLA/Flax). The first type is a pure laminate. The second, third and fourth types incorporate polymer interlayers (polypropylene – “PLA+PP” or polyamide – “PLA+PA”) to improve and facilitate the adhesion between the copper layer and the substrate. The different types are presented I Table 1.

TABLE I. TYPES OF INVESTIGATED BOARDS

FR4	Reference board
PLA	PLA/Flax without interlayer
PLA+PP_1	PLA/Flax with polypropylene interlayer 1
PLA+PP_V2	PLA/Flax with polypropylene interlayer 2
PLA+PA	PLA/Flax with polyamyde interlayer

The general structure of the investigated substrates is illustrated in Fig. 1.

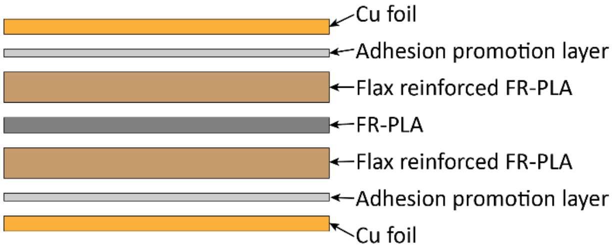

Fig. 1. General structure of the biodegradable substrates

B. *Measuring the copper adhesion*

The peel strength of the copper layer was measured using a standard test pattern described in the IPC-TM650 standard [6]. The test pattern consists of a 4 mm wide copper track and a slightly larger rounded part to be fixed into the test equipment during the peeling. The test pattern is shown in Fig. 2.

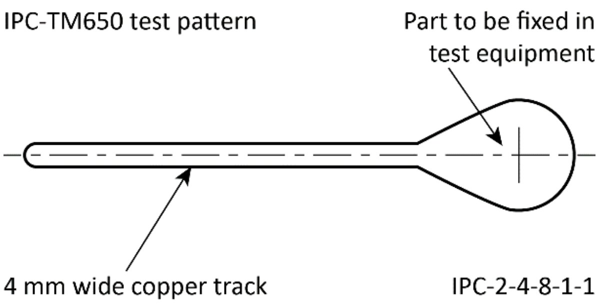

Fig. 2. Copper peeling test pattern based on IPC-TM650-2-4-8-1-1

During the test run, care should be taken to pull the sample vertically. Deviations from the vertical angle can cause measurement errors. However, this measurement error can be decreased by carefully analysing the results. Still, we determined to construct a piece of custom-made sliding equipment to allow the vertical peeling of the copper layer (Fig. 3). The custom-made sliding sample holder is presented in Fig. 4.

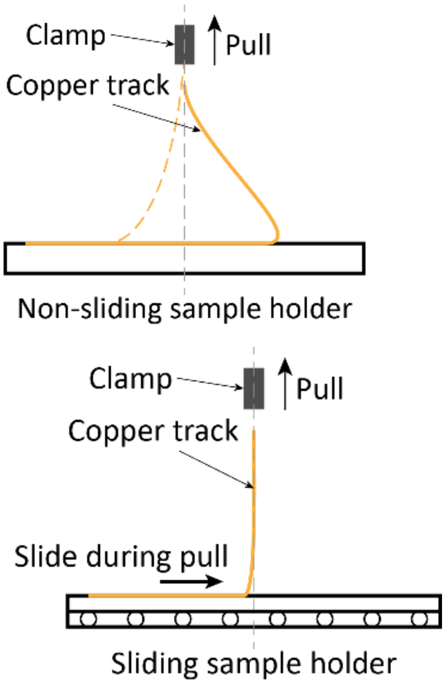

Fig. 3. Copper peel test with (top) and without (bottom) a sliding sample holder

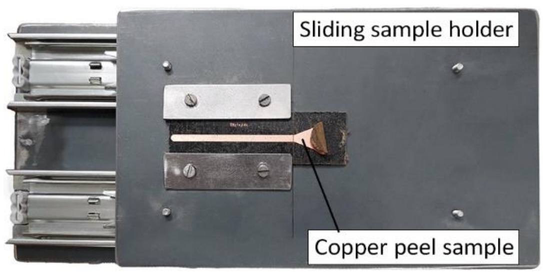

Fig. 4. The custom-made sliding sample holder

The copper peeling was performed using 5965 test equipment (Fig. 5.), and the applied load was recorded automatically. The peel-off speed was approximately 0.83 mm/s.

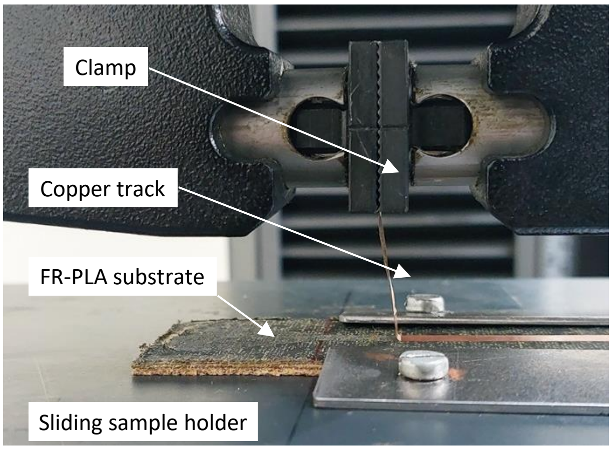

Fig. 5. Peel-off of the copper layer on biodegradable substrate

C. *Investigating the shear strength of solder joints*

The shear strength of solder joints has also been investigated. Surface-mounted resistors of three sizes were soldered to soldering pads covered with electroplated tin surface finish. The component sizes were 0805 (2 × 1.27 mm^2), 0603 (1.5 × 0.75 mm^2), 0402 (1 × 0.5 mm^2). The solder alloy in the solder paste was a low-melting-temperature SnBi alloy (Sn42/Bi57.6/Ag0.4) with a liquidus point of 138 °C. The solder paste (Type-4 – particle size range is 20–38 µm) has been deposited with a 175 µm thick stencil; the components were placed with a semi-automatic placement machine (TWS Laser Quadra), and the soldering was carried out in an EC-Reflow-Mate infrared, batch-type oven. The reflow thermal profile is illustrated in Fig. 6. The peak temperature was 165 °C, the time to peak temperature was approximately 180 °s, while the time above liquidus (TAL) was 228 s.

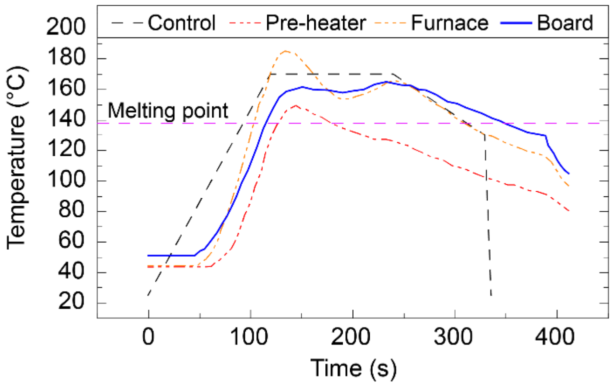

Fig. 6. Reflow profile for the SnBi low-temperature solder alloy

The shear strength values of the solder joints were measured with a Dage-2400 equipment using 200 µm/s shear speed after soldering.

III. Results

A. *Copper adhesion test*

First, the copper peel strength of FR-PLA substrates was analysed. The peel strength was determined by fitting a regression line to the measurement result (over time) and then calculating the average of the fitted data set. This approach was followed to eliminate any minor slope in the measurement results because of minor deviations from the vertical axis during the load. An exemplary result of a PLA/Flax ("PLA" according to Table 1.) board is illustrated in Fig. 7.

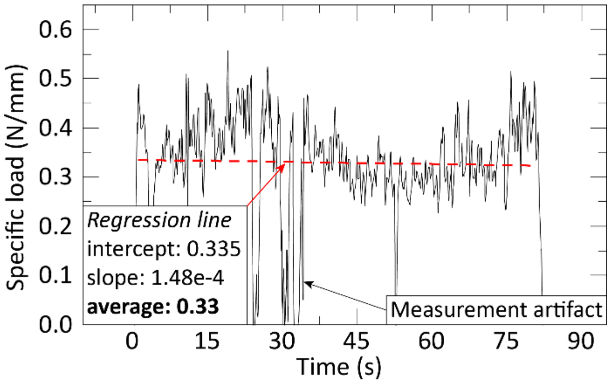

Fig. 7. Evaluation of peel strength results (pure PLA board as an example)

The "PLA" boards and those with polypropylene interlayers ("PLA+PP_1" and "PLA+PP_V2") exhibited relatively low specific peel strength (pull force divided by the width of the copper track), though the values agreed with the literature data. The specific peel strength was approximately 0.4 N/mm for these substrates. By analysing the peeled-off copper tracks, no sign of PLA or adhesion promotion layers could be observed on the bottom side (Fig. 8). This means that the copper was very easily detached from the substrate.

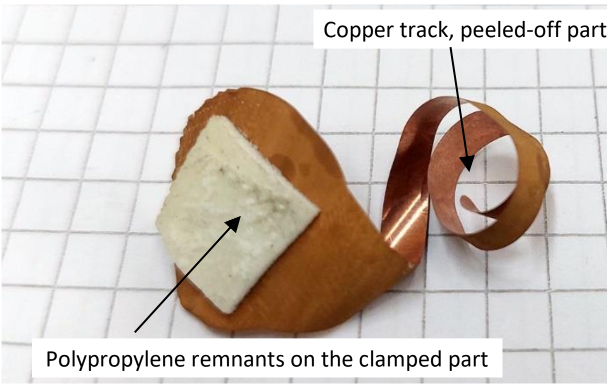

Fig. 8. Copper track peeled off from an FR-PLA/Flax board with polypropylene adhesion promotion layer

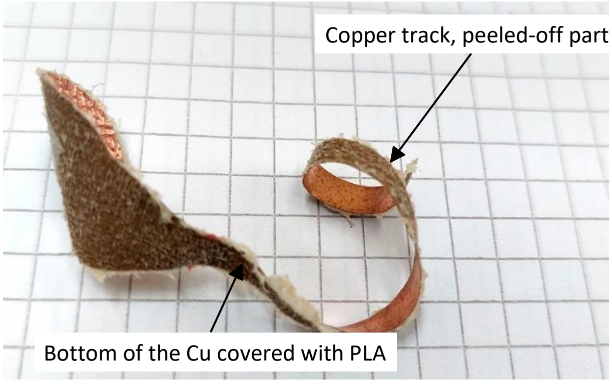

Fig. 9. Copper track peeled off from a FR-PLA/Flax board with polyamide adhesion promotion layer

On the contrary, very high specific peel strength was acquired by using polyamide as the adhesion promotion layer. The average specific strength was about 3 N/mm, which is actually twice the reference value (~1.5 N/mm for standard FR4 boards). The bottom side of the peeled-off copper was covered entirely with PLA (and the adhesion promotion layer in between them), implying that the delamination occurred between the inner layers of the substrate (laminate). Figure 9 shows an example of the bottom side of a copper track peeled off from these substrates. The summary of the specific peel strength is illustrated in Fig. 10.

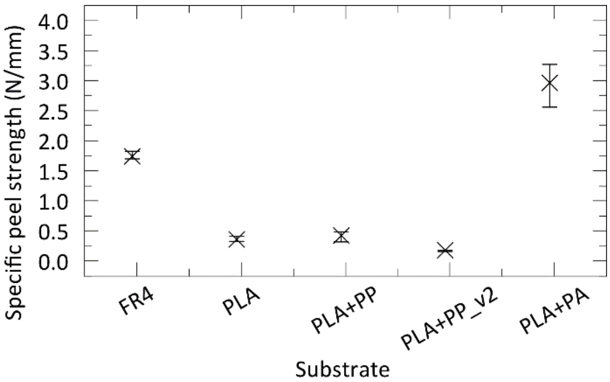

Fig. 10. The specific peel strength of the different biodegradable substrates compared to a standard FR4 reference

B. Solder joint shear strength

The shear strength of solder joints of three different size surface mounted resistors (0402, 0603, 0805) assembled on three substrate types (FR4 – reference, "PLA" – biodegradable reference, "PLA+PA" – substrates with polyamide Cu adhesion promoting layer) has been analysed next. Note that the shear force results for all types of failure forms (pad-lifting, solder joint cracking, component cracking) were merged to examine the entire structure (substrate + soldered components) as a whole. In the case of 0402 size resistors, the shear force of solder joints on both types of biodegradable substrates was almost the same (slightly less than 10 N) and below the reference value of FR4 (~13–14 N). The polyamide adhesion-promoting layer apparently did not contribute to a significant increase in the shear force. However, other artefacts can also affect the shear force of solder joints in the case of small-size components. Namely, the errors in solder mask positioning can be higher in the case of biodegradable substrates because of their slightly wavy surfaces.

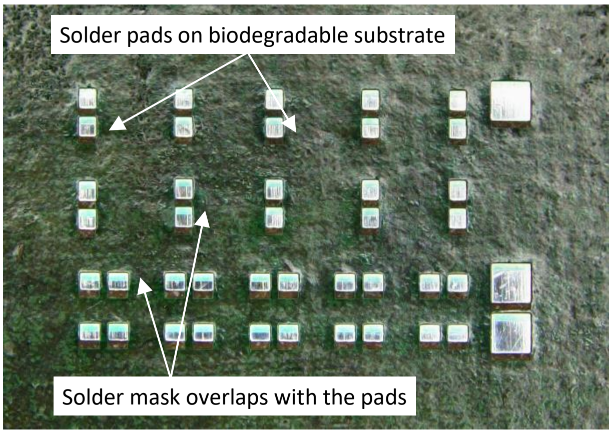

Fig. 11. A specific case of solder mask positioning inaccuracy, the mask overlaps with the solder pads, thereby reducing the effective contact area for soldering

The positioning error of solder mask openings (a specific board with major error, as an extreme example shown in Fig. 11.) results in a smaller contact area between the solder joints and the solder pads, leading to lower mechanical bearing surface and shear force values. In the case of 0603 and 0805 size resistors, the mean shear strength on pure PLA substrates was quite low (less than 20 N, even for 0805 size resistors). However, the Cu adhesion-promoting layer has a definite positive effect on the shear strength of the solder joints at these resistors. The shear strength of 0603 resistors' solder joints reached even the reference strength of those formed on FR4 substrates. The overview of the shear forces in various substrate-resistor combinations is illustrated in Fig. 12.

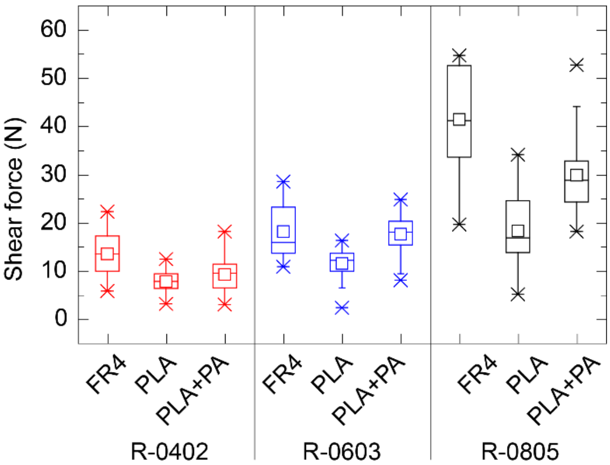

Fig. 12. Shear forces of solder joints at different size resistors assembled on standard FR4 and biodegradable substrates

IV. Conclusions

The copper peel strength and shear strength of solder joints were characterised using biodegradable flame retarded PLA/Flax substrates. Polylactic acid substrates incorporating polyamide adhesion promotion interlayer can effectively increase the copper peel strength (where bio-polyamide [7] application is a path for the future) The specific peel strength of the copper layer on these biodegradable laminates can reach values that are in accordance or higher with those of the reference FR4 substrates. The copper adhesion-promoting layer has a positive effect on the shear strength of solder joints, too. Finding biodegradable alternatives to the adhesion-promoting interlayers is suggested to be the focus later on. Additionally, the solder mask positioning inaccuracies (on biodegradable substrates with wavy surfaces) should be addressed – the textiles are need to be refined design rules for solder mask opening should be revised. The refined core substrate was already introduced in [8]; the future investigations will continue with such boards. Design rule considerations for biodegradable substrates will be elaborated in future work. The work serves as a pilot study, where the methodology can be extended to various sustainable substrates.

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