Current carrying capacity of PCB traces on PLA/Flax biodegradable substrates

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Abstract—In this study, the thermal behaviour of copper traces on PLA/Flax (polylactic acid with flax textile reinforcement) composite-based biodegradable printed circuit board (PCB) substrates were examined. The goal of the study was to investigate the applicability of the calculations based on the IPC2152 standard on the sustainable substrates. To examine the adoption of the standard, we prepared test panels with traces of stepwise width increase (8-40 mil) on both the PLA/Flax and reference FR4 substrates. We measured the temperature change as a result of driving pre-specified levels of current through the traces. From the collected data we can illustrate the differences and similarities compared to widely used PCB substrates, such as the traditional FR4 or polyimide. It was found that the obtained results of PLA/Flax substrates show similar performance to traditional substrates.

Keywords— biodegradable PDB, IPC2152, trace width, sustainable electronics, current carrying capacity, thermal camera

I. Introduction

The number of electronic devices used worldwide raised a significant problem regarding e-waste management. The world generates over 60 million tons of e-waste yearly [1] of which 42% is the printed circuit board (PCB) substrate [2]. And while biodegradable PCBs could have a positive impact on the problem [3], implementing them is not trivial [4]. Most industry standards and processes are built around the widely used substrates such as glass fiber-epoxy composites (e.g. flame-retardant class 4: FR4) and polyimide. Being able to adopt various standards would make the designing process on the biodegradable substrates more flexible.

The main aim of the experiment documented in this paper is to measure the current carrying capacity of flame-retarded PLA-flax (polylactic acid) PCBs (printed circuit boards) and compared to its widely used counterparts (for example: FR4, polyimide). Current carrying capacity is a key aspect of printed circuit design, especially in high power applications, or where miniaturization is a key. Modern circuit boards are getting more and more complex with higher component density and significantly higher layer count. To keep PCBs as compact as possible it is essential to use the smallest possible trace widths. This raises the question of the thermal effect originated from the current in conductors with smaller cross section. Also, in power electronics designs, the relatively higher currents, and resulting trace heating must be taken into consideration. A bigger cross section means a lower resistance (as seen in equation 1) allowing for less power dissipation on the given conductor (as seen in equation 2).

$$R = \rho * \frac{l}{A}, \quad (1)$$

where R is the resistance [Ω] A is the cross section [m], ρ is the resistivity [Ω*m], l is the length of the conductor [m]. Equation two is presenting the power.

$$P_d = R * I^2, \quad (2)$$

where P_d is the Joule heating power [W], and I is the current through the conductor [A].

Finding the sufficient trace width became a simpler task with IPC standards. The IPC-2221 and the following IPC-2152 standards give an industrially accepted estimate from given parameters in terms of safe use and resulting temperature increase. These standards can be implemented using one of the many free online calculators [5,6].

The main goal of standards regarding the current carrying capacity of a given trace was to find a connection between three different basic parameters. The width of the trace, the maximum allowed temperature change, and the maximum current that would continuously flow through the trace.

Since 2009, the IPC-2152 standard became the prominent standard for sizing conductors on a PCB. The predecessor of the standard, namely the IPC-2111, was found to give incorrect estimates for real life applications, as it did not account for many qualities of the design. The new IPC-2152 standard presents results, that summarize the relationship between the following quantities: thermal conductivity, PCB thickness, distance to a nearby plane and the plane area, copper weight (thickness), trace width, expected or required temperature rise above ambient, and internal vs. external traces.

The results are summarized in a set of charts for internal and external traces and different copper thicknesses, but there is no explicit formula to calculate the expected temperature rise in a PCB trace. However, it is possible to pick data from the chart and develop a mixed power law model [7]. The resulting formula is used to calculate the cross-sectional area (which at a given copper thickness can be converted into width) of the trace for a maximum temperature rise above ambient (ΔT) and current (I):

$$Area = (117.6\Delta T^{-0.913} + 1.15) * I^{(0.84\Delta T^{-0.108} + 1.159)} \quad (3)$$

The formula (eq. 3) given above is the basis of most available online calculators [5,6]. These give designer the possibility to get a good baseline estimate of the minimum trace widths needed to be implemented.

The IPC-2152 standard gives a reliable estimate for the trace width, given that the design uses either a FR4 or a polyimide core. It is established that the temperature differential is only approximately 2% between the two materials when the same trace width is applied, and equal current intensity is applied. Nevertheless, the standard is limited on any guidance on how to adapt it for materials with significantly different thermal conductivity. To address this issue, we wanted to collect data on the novel substrates (based on PLA and flax reinforcement with flame retardants [4]) and determine if there is a direct correlation between the data collected in the standard and the measured data.

II. EXPERIMENTAL – THE TEST PANELS

The measurement process was conducted on custom test PCBs fabricated on the aforementioned flame-retarded PLA/Flax substrates [4]. In the case of real-life scenario PCB designs, the distance between traces is sufficiently small such that the individual heating of the traces affects each other. To investigate separate traces, the traces on the test panel were arranged in a manner that prevented thermal coupling between them. The spacing between these traces was set at 1 inch apart, while the distance from the edge of the panel was calculated to facilitate symmetrical dissipation of heat. This approach was adopted to ensure the accuracy and reproducibility of the experimental results [6]. The layout of the panel is shown on Figure 1. The layout design is based on the following trace widths: 8, 10, 12, 14, 16, 18, 20, 24, 28, 32, 36 and 40 mil.

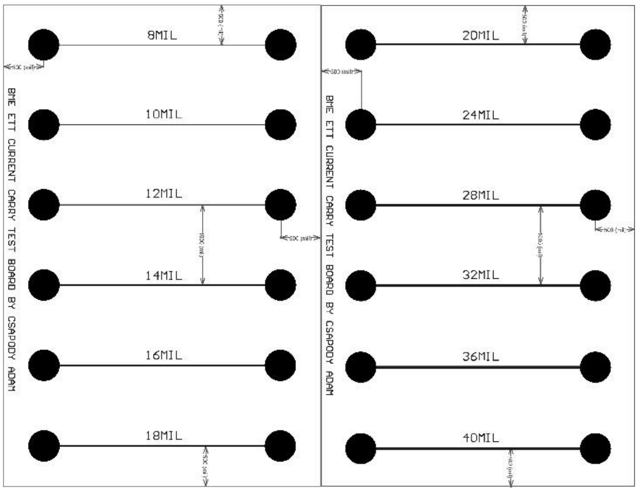

Fig. 1. The PCB layout of the test panels with dimensions.

The physically realized panels (which were produced with subtractive PCB technology, based on a dielectric core, laminated with 35 µm thick Cu foils) are shown in Figures 2 and 3. Figure 2 presents the initial form of the panels. It should be noted that the use of a thermal camera can cause impractical issues, unable to provide reliable readings on shiny metallic surfaces. To obtain optimal, a thin, matte black coating (acryl lacquer RAL 9005M professional spray paint) was applied to the panels. The contacts remained free of paint. The emissivity of the paint is approximately 0.92 [8].

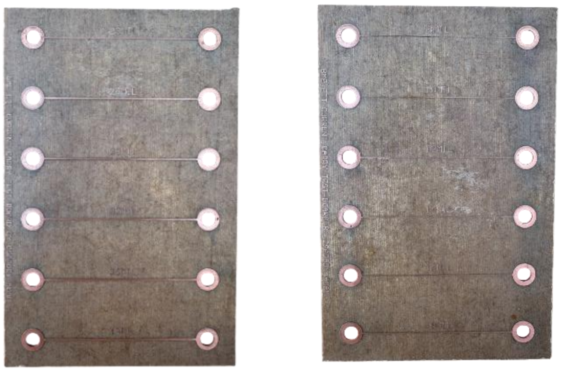

Fig. 2. Right picture: PLA/flax test panel with 8 to 18 mil wide traces , Left picture: PLA/flax test panel with 20 to 40 mil wide traces.

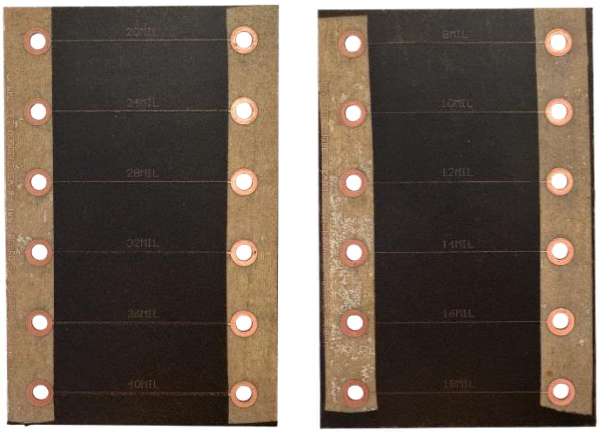

Fig. 3. Test panels with thin matt paint layer applied.

III. EXPERIMENTAL - MEASUREMENT SETUP

The measurement setup consisted of the panels shown in the previous section, a lab bench power supply (GW Instek GPS4303), a stand and an IR camera with an accuracy of ±2°C (Hikmicro Mini 2 Plus) with the emission set to 0.91 ~~(the emissivity of the applied black paint).~~ , a slight correction over the paint's emissivity according to pilot tests. The setup is shown on Figure 4. The driving current was set to 0.5, 1, 1.5, 2, 2.5 and 3 Amps.

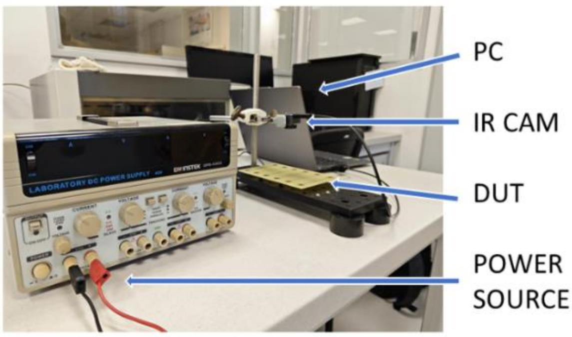

Fig. 4. Measurement setup with the DUT (device under test)

During the measurements, the laboratory ambiance was kept around 20 °C. In addition, all lighting positioned directly above the set-up was switched off to minimise the effect of the surrounding heat on the collected data. However, despite implementing these measures, an anomalous warm spot was observed in the middle of the field of view (FOV) of the camera. The camera was found to be emitting heat, which had a measurable effect on the temperature measurements. To address this issue, the measurement was shifted to the upper half of the camera's FOV (field of view). This adjustment is illustrated in Figure 5.

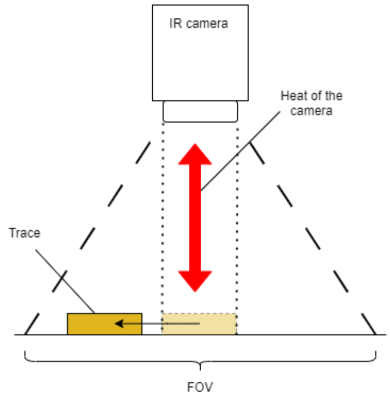

Fig. 5. Problem with heat emitted by the camera, reflected on the resulting image was solved with moving the trace out of the direct view (still within FOV).

In the concluding round of measurements, data was collected from all traces apart from the 8 and 10 mil (as these were eventually overdriven and underwent a substantial resistance change). The data collected from driving 0.5 and 1 Amps was omitted during the evaluation process, as it resulted in temperature changes that were comparable to the error margin of the IR camera (±2°C) when applied to wider traces.

The data was collected using the “Hikmicro analyzer” software provided by the manufacturer of the camera. The software facilitates the placement of shapes on top of the thermal picture. The user is able to collect the maximum, minimum and average temperature of a drawn shape over time. However, for the purpose of comparison with the IPC-2152 standard, it is sufficient to consider the maximal temperature change from ambient. Data was collected by measuring the average temperature of square drawn around most of the length of the trace, as shown on Figure 6.

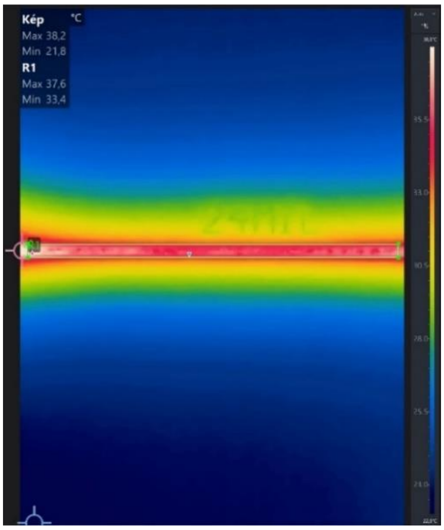

Fig. 6. Hikmicro analyzer software user interface showing the temperature distribution of the 24 mil trace while driven. Colors from red to blue correspond to temperatures from hot to cold respectively, according to the legend on the right side of the image.

At the stage of the research with PLA/Flax boards, it must be noted that the manufacturing of printed circuit boards on the PLA/Flax substrate is subject to higher tolerances. To this end, all traces were measured in order to obtain the actual width and the final copper thickness (after the plating of vias). The collection of these values was performed by employing a stylus-type profilometer (Alpha-Step 500). This approach enabled a direct comparison of the measured data with the standard by using the actual trace dimensions.

IV. Results

Prior to the analysis, it was necessary to correct the data collected from the test panels, which had been constructed using a 1.25 mm-thick experimental board. In comparison to this, the panels used for the standard were composed of a 1.79 mm-thick board. The utilisation of a thinner board results in higher measured temperatures, due to the reduced material available for the dispersion of the dissipated heat. The standard describes an approximate linear relationship between the percentage difference in board dimensions and the percentage difference in temperature. According to IPC-2152 [8], "Current carrying capacity testing of conductors in 0.965 mm [0.038 in] thick FR-4 PCBs show results that are 30-40% higher in temperature compared to the 1.79 mm [0.070 in] thick PCB temperatures. The higher temperatures (a 40% increase) are seen in larger conductors (2.54 vs. 0.203 mm [0.100 vs. 0.008 in]). Testing with 1.50 mm [0.059 in] thick FR-4 PCBs showed temperatures that are 10-20% higher compared to the 1.79 mm [0.070 in] thick polyimide test boards."

We collected the height of each trace as measured height/34.8 (thickness of 1 oz copper foil in µm) shown on Figure 7. This diagram gives a visualization of the additionally galvanized Cu on the top of the starting foil thickness, and the manufacturing uncertainty of trace thickness on the PLA/Flux substrate. We calculated and used the mean of these measurements for the collection of data points from the standard.

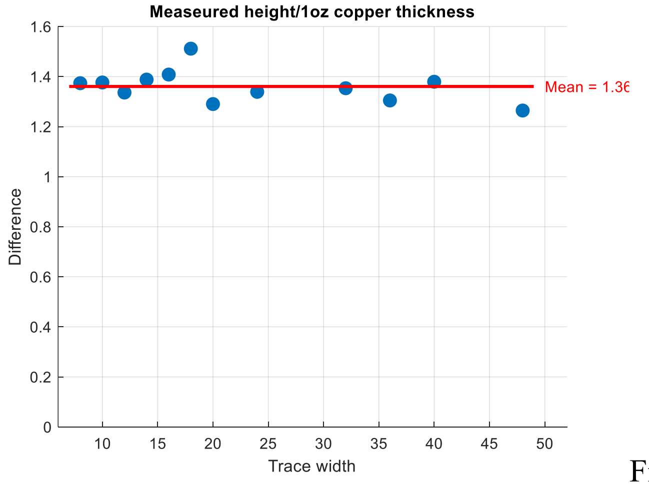

Fig. 7. Measured trace height against 1 oz copper foil thickness

For each current value, the measured data were compared with the corresponding values from the standard (Figure 8). The standard reference values were selected based on trace dimensions matching those of the test board. Since the actual copper foil thickness was not exactly 38.4 µm (nominal 1 oz), the real measured foil thickness was used to determine the appropriate reference data points from the standard. Furthermore, the difference was calculated as a percentage for each curve (Figure 9).

To evaluate these results, a control measurement was made. Utilising the same design shown in Figures 1-3 but using FR4 as the base material. It is important to note that, as previously mentioned, the values in the standard were collected on a polyimide board. The standard indicates that there is a 2% difference between the data and the expected temperature change on FR4. Taking that into account the outcome of the control measurements illustrated in Figure 10, demonstrates a similarity to the data derived from the standard.

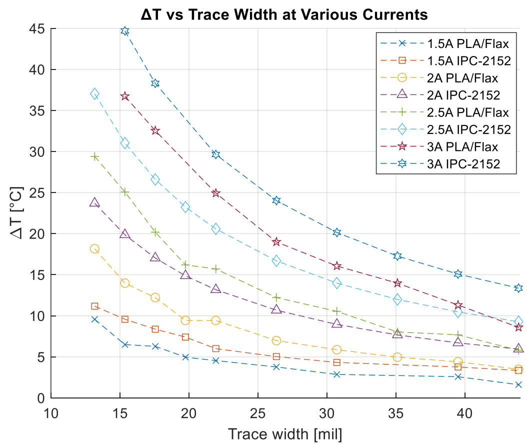

Fig. 8. Comparison of the measured data with the standard reference data.

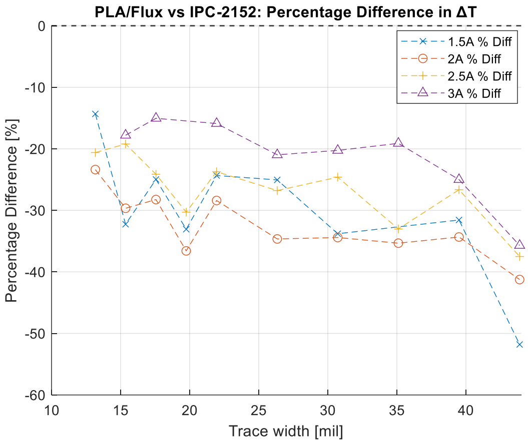

Fig. 9. The precentage difference between the IPC-2152 standard and the measured data points

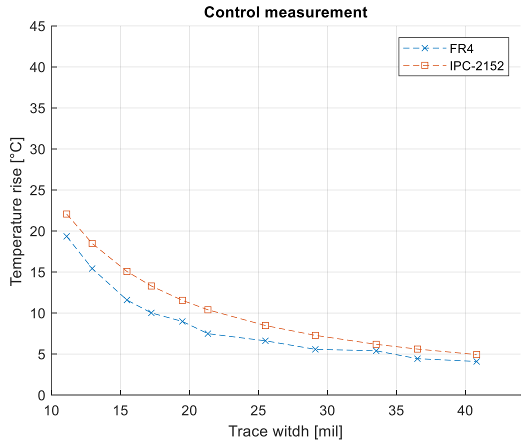

Fig. 10. Results of control measurement with FR4-based PCB

The mean difference was also calculated for each current value (1-3A) for the PLA/Flax boards and the standard based calculations. The bar chart presented in Figure 11 provides a visual representation of these values.

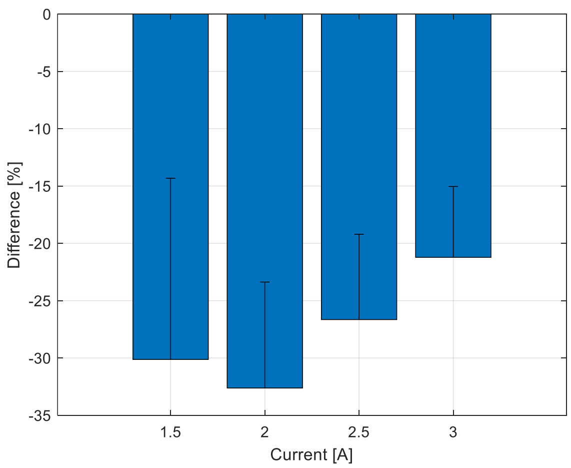

Fig. 11. Mean difference of data points for each current value.

As the data displayed in Figure 10 is consistent, an aggregate mean of 28% was determined. This finding indicates that the same trace on the PLA/Flax substrate heats up less suggesting that the PLA/Flax substrate provides more effective heat conduction than the FR4 board.

This brings questions for further discussions. According to the standards [8], the FR4 has a thermal conductivity of 0.488 W/mK. According to various web-based sources, it can be said, that an approximate thermal conductivity of the FR4 in the in-plane aspect (X-Y direction) is 0.25-0.30 W/mK. It has to be noted that the through-plane (Z direction) is considerably less 0.10-0.20 W/mK [9]. The standard overestimates the data from other sources.

The polyimide has very similar values to Z-dimension conductivity of FR4: 0.12 W/mK [10]. The thermal conductivity of PLA is also similar, 0.12-0.13 W/mK [11,12] So, either the used FR4 material has slightly lower thermal conductivity, or the PLA/Flax composite has slightly better thermal conductivity or diffusivity. This has to be investigated in the future to establish firm connection between the ~25% difference of measured values and standard-based calculations. While copper has a much higher thermal conductivity (larger with three ranges, 401 W/mK), the PCB core aspect of the thermal behavior has to be investigated further.

V. CONCLUSIONS

The measurements were successful, and we were able to make an applicable comparison with existing data from standards used throughout the industry. Following the initial optimisation of the measurement setup, reliable and reproducible results were obtained.

The final result indicates a relationship between the PLA-flux and polyimide or FR4 substrate thermal behaviour. Consequently, the existing standard can be utilised in applying the calculated difference of 28%, which means that traces on the PLA flux board will heat up ~28% less than those on an FR4 or polyimide one. This has to be investigated in future experiments; however, it must be said, that the measurements are close to the results obtained with traditional FR4 and polyimide materials, meaning similar current capacity performance.

The results demonstrate a promising future for the use of PLA-based biodegradable substrates as core materials for the manufacture of printed circuit boards. The successful implementation of a widely adopted industry standard with a single multiplier further increases the possibility of using such a material for a wide range of applications. In the follow-up works, obtaining measurements on different PLA/flax generations are in our focus, combined with validated thermal conductivity measurements.

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REFERENCES

[1] Igini, M. Less Than 25% of Global E-Waste Is Recycled, UN Report Warns. Earth.org. https://earth.org/e-waste-recycling-rates-remain-dangerously-low-as-demand-for-electronic-devices-booms-un-report-reveals/ (Accessed at. 2025. 02. 01.)

[2] M. Chakraborty, J. Kettle and R. Dahiya, "Electronic Waste Reduction Through Devices and Printed Circuit Boards Designed for Circularity," in IEEE Journal on Flexible Electronics, vol. 1, no. 1, pp. 4-23, Jan. 2022,

[3] A. Géczy, L. Gyenizse, C. Farkas, D. Rigler, B. Sáfár and A. Csiszár, "Biodegradable PCBs with PLA/Flax Substrate: FTIR and SEM Analysis of Soil Degradation," *2024 IEEE 10th Electronics System-Integration Technology Conference (ESTC)*, Berlin, Germany, 2024, pp. 1-6, doi: 10.1109/ESTC60143.2024.10712063.

[4] Géczy, A., Piffkó, D., Berényi, R., Dusek, K., Xavier, P., & Cuartielles, D. (2024). Implementation of microcontroller board on a sustainable and degradable PLA/Flax composite substrate: a case study. *Nanotechnology*. https://doi.org/10.1088/1361-6528/ad66d3

[5] ProtoExpress. *PCB Design Tool – Trace Width Calculator*. https://designertools.app.protoexpress.com/?appid=TWCCCAL(Accessed 2025. 03. 26)

[6] Z. Peterson,” Using an IPC-2152 Calculator: Designing to Standards”https://resources.altium.com/p/using-ipc-2152-calculator-designing-standards (Accessed at 2025. 03. 26.)

[7] Smps.us: “CALCULATION OF PCB TRACE WIDTH BASED ON IPC-2152”, https://www.smps.us/pcb-calculator.html (Accessed: 2025.03.26)

[8] Jandrlić, I. & Rešković, S. Choosing the optimal coating for thermographic inspection. Holist Approach Environ. 5, 127–134 (2015)

[9] IPC, "Standard for Determining Current-Carrying Capacity in Printed Board Design," IPC-2152, IPC Association Connecting Electronics Industries, Bannockburn, IL, USA, 2009.

[10] RayMing Technology. "PCB Thermal Conductivity Performance: FR4 Vs. Ceramic Vs. Metal Core Vs. Rogers." *RayPCB*, https://www.raypcb.com/pcb-thermal-conductivity-performance-ceramic-pcb-vs-metal-core-pcb/. (Accessed: 2025.04.18)

[11] Massachusetts Institute of Technology, "Polyimide – 6.777J/2.751J Material Property Database,", https://www.mit.edu/~6.777/matprops/polyimide.htm. (Accessed: 2025.04.18)

[12] SEAS 3D Print. "PLA Technical Data Sheet." SEAS 3D, https://www.seas3d.com/MaterialTDS-PLA.pdf. (Accessed: 2025.04.18)

[13] O. Zmeškal, L. Marackova, T. Lapcikova, and P. Menčík. "Thermal properties of samples prepared from polylactic acid by 3D printing." *AIP Conference Proceedings*, vol. 2305, no. 1, pp. 020022, 2020. https://doi.org/10.1063/5.0033857. (Accessed: 2025.04.18)