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ORIGINAL ARTICLE

Low-cost and novel Arduino®-Load cell-based prototype to determine transition temperatures

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Abstract

The polymer transition temperature is a crucial parameter in the industry for knowing raw materials before starting the manufacturing process. The current work reports a novel low-cost prototype instrument to measure the transition temperature with reliable accuracy. The equipment was built using commercial load cells composed of strain gauges in combination with an Arduino® microcontroller. The prototype measurement quality was validated by measuring the transition temperatures of most commercial polymers. The obtained values were compared with values obtained by conventional thermal analysis known as differential scanning calorimetric and thermo-mechanical analysis (DSC and TMA), which results in identical values.

Keywords: *Arduino®, load cell, polymer transition, DSC, TMA.*

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1. Introduction

The transition temperature is an important parameter that can be applied to polymers which contribute to determining their application in manufacturing. According to the morphology, thermoplastics can have either one or two possible transitions: glass-transition temperature (Tg) and melting temperature (Tm). The first is present for polymers with a predominant amorphous structure and the second is when the structure is crystalline. Meanwhile, polymers with the semi-crystalline structure showcase both Tg and Tm[1]. When a polymer is heated up, any of these transition temperatures are reached and it changes in properties like specific volume and heat capacity[2]. The glass transition is a second-order change, it occurs when the ends of the polymeric chains initiate a vibration, with the consequent change to rigidity, hardness, and/or brittleness. Due to these transitions, polymer materials can be evaluated with different thermal techniques[3]. Commonly used thermal analyses to characterize polymers are differential scanning calorimetric (DSC) analysis, dynamic mechanical analysis (DMA), thermo-mechanical analysis (TMA), and dielectric thermal analysis (DEA)[4]. For the plastics industry, the importance of Tg and Tm involves two aspects. First, it is to establish the processing temperatures for the injection and molding[5]. The second is about characterizing and identifying each polymer. A frequent problem in the plastics industry is the inter-change of raw materials generating mistakes. This problem occurs mainly in factories, which use many types of raw materials. Sometimes this problem is not easily detected. For example, when two polymers with clearly different processing temperatures are mixed, resulting in a nozzle obstruction or slow flow during the injection. Unfortunately, this phenomenon is not detected just when the final product reaches the customers. These products present faults up to break, due to the mixing of pellets with different amounts of filler[6].

The common thermal analysis instruments to characterize polymers are expensive, with prices of around 30,000 USD. It is an expensive inversion for medium and small companies. There is also the alternative of paying out-services for these analyses through certified laboratories. However, this option becomes unprofitable when the test numbers increase.

The purpose of this work is to design a novel prototype to measure transition temperatures with high precision and low cost. This prototype is made with commercial load cells (strain gauges)[7,8] in combination with an Arduino® microcontroller. The sensor module is a platform based on open-source software and hardware, widely used by developers due to its high flexibility for measurement and control projects[9]. The prototype was validated by measuring transition temperatures for four different commercially available polymers. These values were compared with data obtained by TMA and DSC techniques[10].

2. Materials and Methods

2.1 Materials

Acrylonitrile butadiene styrene (ABS) and polystyrene (PS) were used to perform the glass transition temperature (Tg) measurements. While polyoxymethylene (POM) and high-density polyethylene (HDPE) were chosen to measure melting temperature (Tm). All materials were brand Henkel.

2.2 Thermal characterization

Comparative thermal analysis was made by DSC and TA Instruments model Q200, with a heat-up and cool-down cycle range from 25 °C to 200 °C. The DSC and TMA measurements were obtained three times for each sample. The heating ramp was programmed at 10 °C/min in an inert atmosphere with a volume flow of 50 Ncm^3/min. Meanwhile for thermo-mechanical analysis (TMA) was used TA Instruments model Q400. The same heat ramp was used in DSC, reaching 200 °C, and an applied load of 0.1 N with a penetration probe. ASTM D3418 standard was followed for DSC measurement to determine the middle points in slope change of glass-transition temperature for ABS and PS[11]. However, in the case of endothermic fusion HDPE and POM were considered the middle point. ASTM E1545[12] standard was followed for TMA analysis to assign temperature points where dimensional changes correspond to glass-transition and fusion points.

The polymer probes to measure by prototype were sheet plates with 10 × 10 mm dimensions and a 1.5 mm thickness. These plates were put on top of an internal oven platform (Figure 1). Over the plates, a probe with a penetration tip was placed and adjusted to an approximate load of 1 N by a calibrated spring. The oven was programmed with a heating ramp of 10 °C/min, starting from room temperature to 200 °C.

2.3 Prototype

An Arduino® Mega 2560 microcontroller was used for data processing and storage. For deformation data reading, a sensor module, cold-junction-compensated with K-thermocouple-to-digital converter model MAX6675, and a 1 kg load cell (brand Sparkfun) plugged into an ADC HX71 24 bits module (brand XFW), were used. These load cells are co-formed by 2 strain gauges placed at the bottom and top. They measure the deformation produced in the load cell by reading the voltage induced in them. These components were connected to the microcontroller to plot data, with the X axis related to temperature, and the Y axis associated with a DC signal response. The heating ramp implemented was 10 °C/min. Figure 1 shows prototype components, which consist of a platform where the Arduino® was placed, while one edge of the load cell is attached to the same platform. The other edge was fixed with a penetration probe that is in contact with the sample.

The sample holder is concentrically positioned concerning the oven hole (Figure 2). It is a platform where a piece of polymer sample to analyze was located and on it was placed the penetration probe of 6 mm in diameter, adjusted at 1 N by a calibrated spring. Close to the sample was placed a K-type thermocouple (TC). It was used to register the temperature of the polymer sample.

3. Results and Discussion

3.1 Acrylonitrile Butadiene Styrene (ABS)

Figure 3a shows DSC and TMA analysis for the ABS polymer. The black dotted vertical line (denoted the DSC) shows a change in the slope of the curve, indicating a glass transition (Tg) of the material at 75.8 °C. While the TMA technique shows the onset temperature at 80.7 °C.

Figure 3b shows the graph acquired for the ABS sample by the prototype. In this case, the signal is a voltage change as a function of the temperature. The dotted line reveals the beginning of a voltage drop in the output signal at 82.1 °C, this was determined by the derivative of the signal voltage drop vs temperature. This value is similar to the TMA measurement. There is a 1.4 °C difference between both instruments.

3.2 Polystyrene (PS)

Figure 4a shows results for polystyrene by DSC and TMA techniques. The value determined by the DSC graph is dotted by the vertical line to locate a change in the slope of the curve. The glass transition is localized at 101.1 °C. It can be noticed, that the signal is weak and it could not be accurate. However, the value determined by TMA is 100.4 °C. In this case at the beginning of the dimensional change; there is a difference of 0.7 °C in comparison to getting by DSC. The glass-transition temperature for this polymer is almost the same value for both techniques.

Figure 4b shows the glass-transition temperature registered by the prototype, the value is 98.6 °C. The glass transition temperature was determined by the change of the slope in the signal drop vs temperature derivative. This value is reflecting a difference of 1.8 °C below the value determined by TMA.

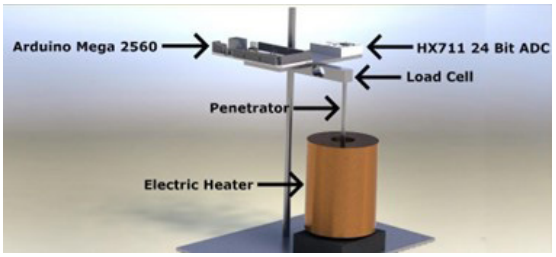

Figure 1. Schematical representation of prototype components.

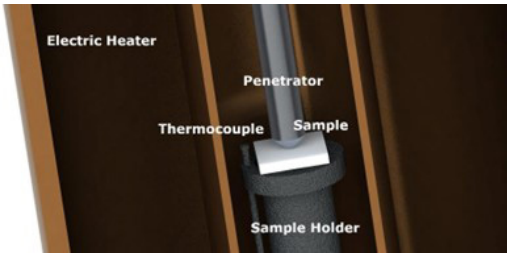

Figure 2. Cross-section view of the sample holder inside the electric heater.

3.3 High-Density Polyethylene (HDPE)

Figure 5a shows the melting transition temperatures for HDPE polymer. For this sample, the DSC behavior is so different. The value is determined by two black dotted lines prolongation crossing. This result agrees with the DSC melting point temperature registered at 129.1 °C. This type of sample is noticed, in contrast to the signal to determine the Tg value (weak slope changing). Meanwhile, the melting point temperature obtained by the TMA technique, onset the value is at 128.9 °C.

The melting transition temperature registered by our prototype is shown in Figure 5b. The derivative of the signal voltage drop vs temperature showed the beginning of the melting point in HDPE. In this case, the value is at 128.8 °C which is below 0.1 °C concerning the TMA technique.

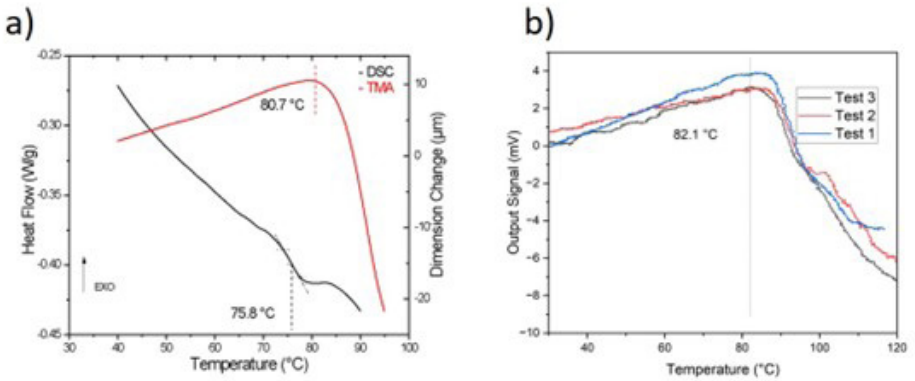

Figure 3. (a) DSC/TMA analysis of ABS; (b) ABS analysis by prototype (load cell-strain gauge).

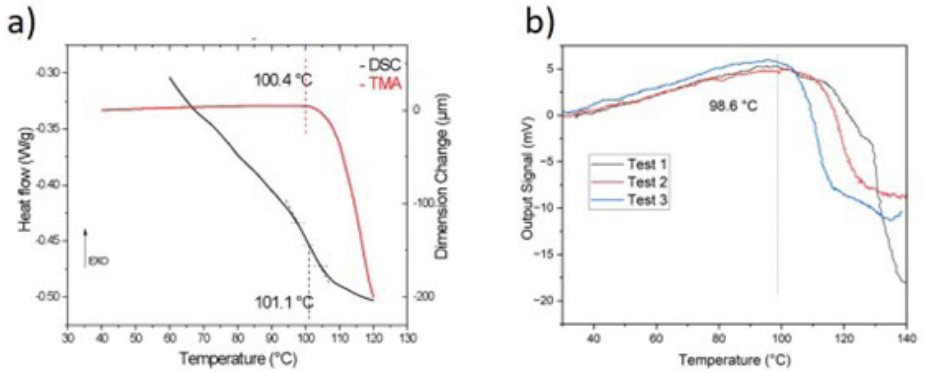

Figure 4. (a) DSC/TMA analysis of PS; (b) PS analysis by prototype (load cell-strain gauge).

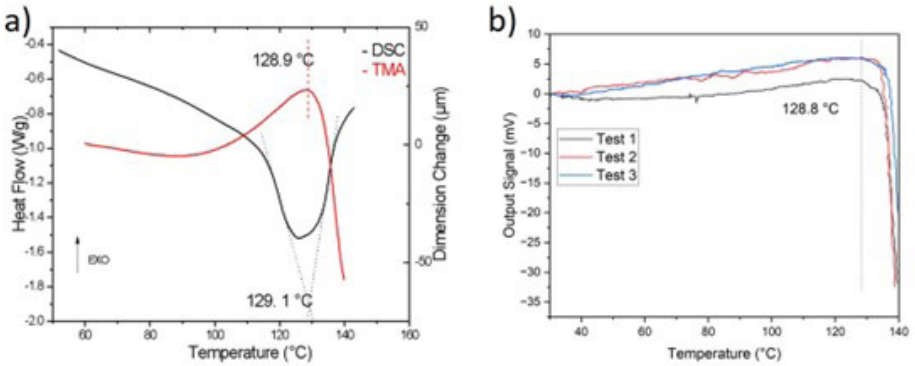

Figure 5. (a) DSC/TMA behavior for HDPE sample; (b) HDPE polymer behavior by prototype (load cell-strain gauge).

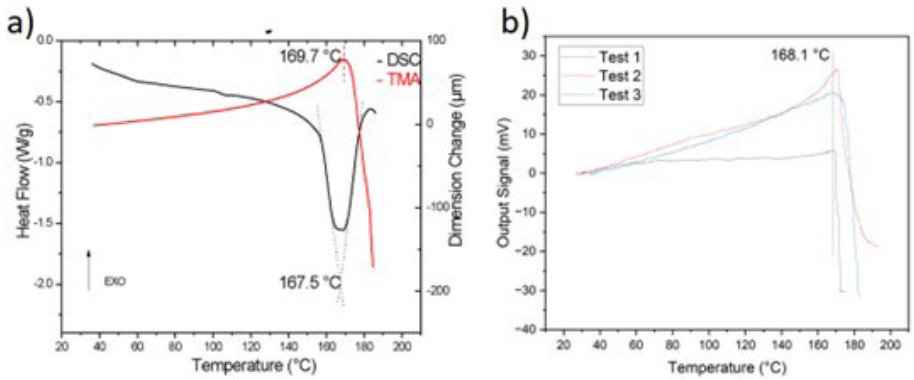

Figure 6. (a) DSC/TMA analysis of POM; (b) POM analysis by prototype (load cell-strain gauge).

Table 1. Comparison between thermo-mechanical analysis (TMA) and prototype measurements.

Polymers	Transition type	TMA (°C)	Prototype (°C)	Variation percentage concerning TMA (%)
ABS	Tg	80.7	82.1	1.73
PS	Tg	100.4	98.6	1.79
HDPE	Tm	128.9	128.8	-0.08
POM	Tm	169.7	168.1	-0.94

3.4 Polyoxymethylene (POM)

DSC and TMA analysis was also performed for the POM sample. Figure 6a shows the melting point temperature. Similar to the criterion for the sample evaluated in Figure 5a, the two black-dotted lines crossing corresponds to the mid-point of the endotherm registered at 167.5 °C. The red-dotted line indicates the beginning of a dimensional change in TMA, corresponding to a melting point, registered at a temperature of 169.7 °C.

The melting temperature (determined by the slope change in the derivative signal voltage drop vs temperature) for the sample POM registered by our prototype is shown in Figure 6b. The value determined is 168.1 °C. This is associated with melting, where a phase starts to change for the polymer POM. There is a 1.6 °C value difference between the prototype and TMA measurement. In general, the signal variation registered in the measurement process by the prototype is clear in comparison to the DSC technique. It is more difficult to determine the Tg value for the polymer samples.

3.5 Transition temperatures comparison between TMA and prototype

There is an evident transition temperature correlation between TMA and our prototype. The values determined by both instruments are adequate to get glass transition and melting temperatures for polymers. This affinity is based on the implemented measurement principle, where the Tg property changes from rigid to soft. A slight penetration of the probe, and in the case of melting temperatures where changes are observed when the material goes into a liquid state. Table 1 shows a comparison of both techniques with the respective percentage errors.

It can be noticed that the prototype values variation percentage from the TMA technique does not surpass 2%. In the case involved the melting temperature did not surpass a 1% variation. Then, it is more effective to determine such temperatures. This becomes logical when dimensional change is measured (in the case of TMA) and voltage variation (in the case of the prototype), which are greater for melting processes than glass transitions.

4. Conclusions

A novel low-cost prototype to perform thermal measurements with reliable accuracy was successfully developed. Four commercial polymers were used to validate the high-precision measurements of this prototype. The values obtained in the current comparison present minimum differences with results obtained by DSC and TMA techniques. The glass transition and melting transition temperature changes exhibit a minimum variation in comparison to data obtained by TMA and DSC techniques. This happens because of the difference in the quantity of energy involved, being the energy for melting is more than the energy for Tg. The most outstanding advantages are that modules can be acquired easily and cheap fabrication costs. For the present prototype, investment did not surpass 500 USD in materials. All used devices make it a reliable low-cost option for micro and small companies working in the plastics industry.

5. Author's Contribution

- **Conceptualization** – Luis Carlos Rodríguez-Pacheco; Daniel Lardizábal-Gutiérrez.
- **Data curation** – NA.

- **Formal analysis** – María Luisa Camacho-Ríos; Luis Carlos Rodríguez-Pacheco; Daniel Lardizábal-Gutiérrez.
- **Funding acquisition –** NA.
- **Investigation** – Guillermo Manuel Herrera-Pérez; María Luisa Camacho-Ríos; Luis Carlos Rodríguez-Pacheco; Daniel Lardizábal-Gutiérrez.
- **Methodology** – Francisco Paraguay-Delgado; Luis Carlos Rodríguez-Pacheco; Iván Alziri Estrada-Moreno.
- **Project administration** – NA.
- **Resources** – Daniel Lardizábal-Gutiérrez; Francisco Paraguay-Delgado.
- **Software** – Rubén Castañeda-Balderas; Luis Carlos Rodríguez-Pacheco.
- **Supervision** – Francisco Paraguay-Delgado; Iván Alziri Estrada Moreno.
- **Validation** – Rubén Castañeda-Balderas; Guillermo Manuel Herrera-Pérez.
- **Visualization** – Daniel Lardizábal-Gutiérrez; Francisco Paraguay-Delgado; Luis Carlos Rodríguez-Pacheco.
- **Writing – original draft** – Daniel Lardizábal-Gutiérrez; Luis Carlos Rodríguez-Pacheco.
- **Writing – review & editing** – Daniel Lardizábal-Gutiérrez; Francisco Paraguay-Delgado; Luis Carlos Rodríguez-Pacheco.

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