

Robust In-Cavity Thin-Film Temperature Sensor Array for Real-Time Flow-Front Monitoring in Recycled Material Injection Molding

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Summary:

We propose a robust thin-film sensing system for in-mold monitoring during injection molding of PP–glass fiber and recycled-content materials. A compact array of resistive temperature sensors is integrated directly on the tool surface with a total layer thickness below 10 μm . The thin-film stack withstands high shear and abrasive glass-fiber flow while showing no drift. Spatiotemporal analysis of the temperature signals across the array provides real-time estimates of local flow-front velocity and direction. Experiments over 500 cycles with varied parameters demonstrate durable operation. The approach supports data-driven process optimization, reduced ramp-up scrap, and future closed-loop process control.

Keywords: injection molding, thin-film sensors, flow-front monitoring, process control

Background, Motivation and Objective

In-cavity sensing is essential for data-driven injection molding. Conventional cavity pressure or temperature sensors are typically bulky, mechanically fragile, and limited in spatial resolution, which restricts their ability to resolve local melt behavior near critical features on the tool surface [1]. Thin-film sensors have previously been successfully integrated into a 2D mold cavity for data-driven quality control in thermoplastic injection molding [2].

We develop a durable multi-sensor thin-film system designed to (i) survive high shear and abrasion for at least 10^5 injection cycles, (ii) fit into highly confined tool geometries, and (iii) provide spatiotemporally resolved temperature data that can be used to infer local flow-front velocity and direction in real time.

Method

A multilayer thin-film system was developed for long-term operation under glass-fiber abrasion. A polished stainless-steel substrate ($R_z = 0.1 \mu\text{m}$) served as the base material for the thin-film system. A 6 μm amorphous hydrogenated diamond-like carbon (DLC) layer was deposited on the tool by plasma-enhanced chemical vapor deposition (PECVD). Round metallic electrodes for resistive temperature sensing were patterned at selected positions using

photolithography from a 0.2 μm chromium layer deposited by physical vapor deposition (PVD). A 1 μm robust insulating amorphous hydrocarbon layer modified with silicon and oxygen (SICON[®]) was then applied using PECVD. The conductive paths were patterned from an additional 0.2 μm thick chromium layer. A 3 μm thick SICON[®] layer was used as a wear-protection layer. The contact areas and lead wires were positioned outside the mold cavity to avoid damage. The total layer thickness was kept below 10 μm , which preserves thermal responsiveness and adds only negligible thermal mass compared with the mold insert. Furthermore, an alternative sensor concept based on an Al_2O_3 -insulated thin-film stack with thermoresistive chromium PTC temperature sensors was implemented on a second mold insert. Its architecture and performance, together with a detailed comparison to the DLC/SICON[®] system, will be discussed in the extended version of this work.

To achieve a high information density in confined regions, the sensor layout was miniaturized so that each temperature sensor has a circular temperature-sensing area with a diameter of 1.6 mm. The four outer sensing points form a square with a side length of about 7 mm (diagonal $\approx 9.9 \text{ mm}$), and the fifth sensing point is located at the center of this square, as shown in Fig.1.

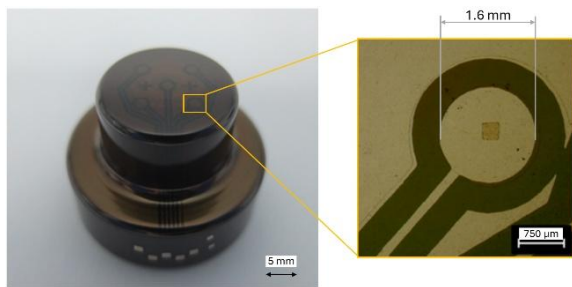


Figure 1. Photograph and close-up of the fabricated sensor system.

To verify the sensor functionality, a thermoresistive characterization was carried out. A Pt100 resistance thermometer was mounted on the surface of the metal insert and served as a reference. The insert with the integrated thin-film sensor system was heated and cooled at a controlled rate in a climate chamber. The measurements revealed an exponentially decreasing dependence of the sensor resistance on temperature over the investigated range.

Sensor signals were acquired using a National Instruments CompactDAQ data acquisition system during injection-molding trials at a sampling rate of 1 kHz. Time-of-arrival and temperature-gradient analyses across the sensor array were implemented to compute local flow-front velocity and direction in real time. As shown in Fig. 2, the thin-film temperature sensor array is arranged on the left half of the mold cavity. The thermocouples are positioned in locations that are mirror-symmetric to thin-film sensors T1, T3, and T4 with respect to the cavity centerline.

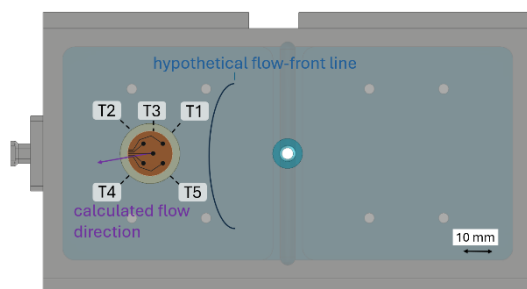


Figure 2. Thin-film sensor system with five temperature sensors installed on the left half of the mold.

Experimental validation was carried out over 500 injection cycles using PP–glass fiber and recycled-content materials with varying levels of recycled content and material quality. Process parameters, including melt temperature, mold temperature, injection speed, holding pressure, and holding time, were systematically varied within industrially relevant ranges.

Results

The thin-film sensors exhibited stable, drift-free signals over 500 shots, with no delamination,

cracking, or electrical failure of the sensor paths. As illustrated in Fig. 3, the temperature curves from the thin-film sensors enable clear identification of the turning points that mark the start and end of each stage in the injection-molding cycle: filling, packing, cooling (after the mold clamping force is released), and demolding. This stage-resolved information can significantly support the maintenance of process stability across batch production for different DOE settings.

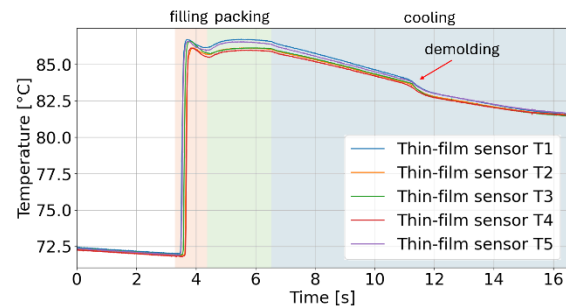


Figure 3. Temperature profiles measured by the thin-film sensor system.

The measured flow-front velocity and direction obtained from the thin-film sensors were compared with those derived from reference sensors, demonstrating excellent agreement. For example, for a high-quality recycled material with 40% recycled content, at a mold temperature of 200 °C, an injection speed of 30 mm/s, a holding pressure of 39 MPa and a holding time of 9 s, the measured average flow-front velocity was 77.4 mm/s at an angle of -85.9° .

In conclusion, this novel thin-film design successfully integrates multiple sensing functions into confined tool spaces without adversely affecting the injection-molding behavior.

Outlook

Future work will further miniaturize the tool insert, increase the sensor count, and integrate the sensing system into closed-loop control strategies with machine-learning-based evaluation in order to enhance process stability and energy efficiency.

References

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