Novel process chain for the integration of printed electronics with microinjection molded plastic parts.

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Abstract

The rise in popularity of printed electronics has led to efforts to integrate it in more established manufacturing methods. Here, we propose an innovative method of integrating printed electronics with thermoplastic micro injection molding. This was accomplished using an ink printing dispensing system that additively deposits traces of conductive ink onto a steel injection mold insert. Once the conductive ink had cured, the insert was placed in the mold and an injection molding cycle was run. The properties of the polymer, as well as the interaction with both the mold surface and the conductive ink would cause the ink to transfer from the mold surface onto the plastic part. Once the cycle had completed, the conductive ink was fully integrated with the plastic part. Tests were performed on the samples to measure adhesion, contact angle, the interaction between the surface and the ink, and surface energy. Further research is being conducted on different geometries for conductive ink traces, and their interaction with different polymers.

Keywords: Molded interconnected devices, additive manufacturing, injection molding,

1. Introduction

Printed electronics commonly manufactured using direct-wire micro-dispensing of conductive inks have been rising in popularity [1]. Standard processes for the integration of these printed electronics within plastic parts are multi-step processes such as insert molding [2], compression molding [3], and overmolding [4]. The printing of electronics on polymer substrates is currently limited in design, and unable to be applied to complex 3D parts with slots or internal surfaces [5] [6]. Additionally, the critical parameters for product functionality include surface roughness, mechanical properties of the electronics, and the structures' adhesion to the surface. Current research on this topic is focused heavily on post-processing methods to increase design flexibility, such as using direct writing to integrate the printed electronics onto the plastic surface [7].

In this work, direct-writing technology is combined with micro injection molding to produce plastic parts with volumetrically integrated printed electronics. The printed electronics are integrated within the plastic part by creating a stronger polymer/ink interface than the mold/ink interface. This promotes the ink to transfer to the plastic part during molding. The integration of the printed electronics within the plastic part is achieved by controlling the surface energies and interfacial strengths through surface coatings [8][9]. This method allows for stronger adhesion between the plastic and the printed electronics. The adhesion is controlled through different phenomena such as surface roughness [10], surface energy [11], and processing [12], with surface roughness being of particular importance, due to high surface roughness allowing the melt to enter voids and increase contact area between the melt and the mold [13].This work proposes a method of producing fully integrated printed electronics within plastic parts through direct-wire printed electronics and combines inkjet dispensing technology with conventional micro injection molding.

2. Materials and Methods

2.1 Insert preparation

To allow the release of the conductive ink from the surface of the insert after molding, the inserts' surface was treated with a coating of ABS (Trilac® ABS-MP1000 Polymer Technology and Services, LLC (PTS), Heath, OH, USA) dissolved in acetone. As shown in Figure 1, a drop of this solution was placed on the mold insert and was uniformly distributed using a spin coater. Both the tensile bar mold and the round insert were coated at 250 rpm. This process allowed a thin and uniform coating to be applied on the surface of the insert. The inserts were subsequently placed on a hot plate at 120°C for 5 minutes to remove any excess solvent.

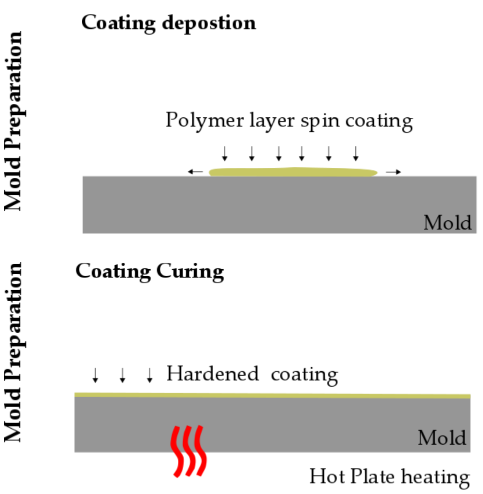

Fig 1. Preparation of the mold insert

2.2. Printing of the conductive ink

The 3D printing of the conductive ink traces was done using silver nano-particle ink (DuPont® CB 028). This silver nano-particle ink was chosen for its frequent use within the field of printed electronics. Following the curing of the coating, the direct wiring was done using an automated micro-pen dispensing system (Nordson Pro4 EFD). Once the conductive ink was printed on the mold inserts' surface, the insert was placed in a vacuum oven (Isotemp, 282A) for sintering at 220°C for 30 min. Trials were conducted on the round inserts in which the sintering of the ink was done at 160°C for 1 hour. The ink traces had a height of 50µm. Each of the traces contained multiple traces stacked on top of each other. Figures 2 and 3 show the setup used during the 3D printing of the conductive ink, and the resulting printed ink traces on the mold insert.

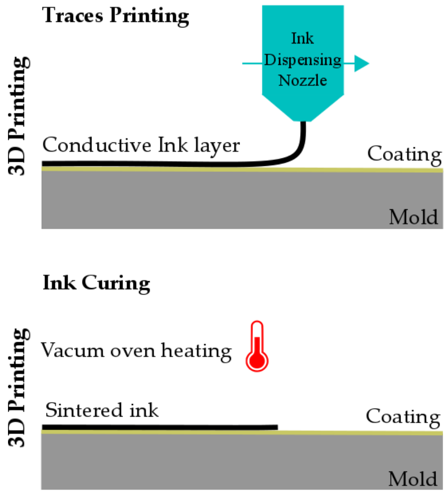

Fig 2. Setup of 3D printing process.

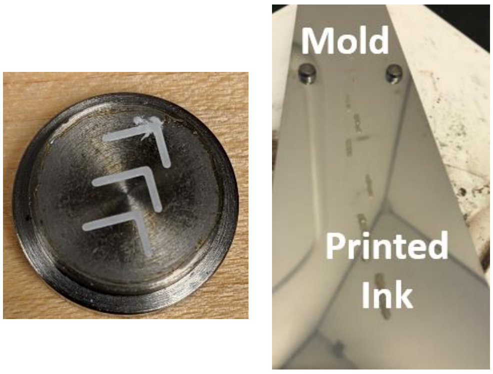

Fig 3. Printed ink on the mold insert surfaces.

2.3 Injection molding setup.

The injection trials for the tensile bar mold were run on a benchtop micro injection molding machine (Xplore® IM 12, Xplore Instruments BV, Sittard, The Netherlands). A steel mold was used to mold ASTM D638-14 type I tensile bars**.** The processing settings that were used for the injection molding trials can be seen in Table 1.

Table 1
Processing settings for injection molding trials.

Settings	Set-Point
Melt Temp (°C)	260
Mold Temp (°C)	80
Hold Pressure (MPa)	0.7
Hold Time (s)	8

The resin used during the injection molding trials was the same ABS used to treat the mold, thus ensuring compatibility with the coating layer [14]. Following each injection molding cycle, the inserts were removed for cleaning, re-coating, and 3D printing. Figure. 4 shows the injection molding process, in which, as the polymer melt flows through the mold, it comes in contact with the sintered ink. During ejection, the sintered ink becomes embedded within the plastic part and is ejected with it.

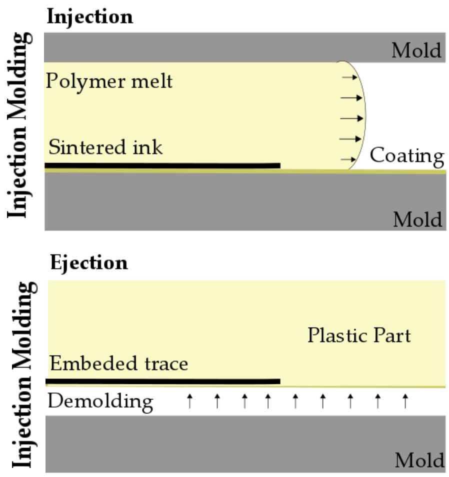

Fig. 4 Injection molding process

3. Characterization and Testing

3.1 Surface Characterization

The traces of the 3D printed ink were observed using a stereomicroscope (Carl ZeissDiscovery V20), and the topographies were obtained using an optical profiler (Wyko NT2000). The surface roughness *Sa,* and mean summit curvature were following ISO 25178:2012-2. The molded parts were cut at several locations to evaluate adhesion and morphology. Figure 5 shows a cross-sectional view of a molded tensile bar with the ink fully integrated within. Additional characterization was done using Scanning Electron Microscopy (Amray 1400 SEM) to better understand the adhesion between the ink and the polymer.

The adhesion between the printed traces and the mold, and the printed traces and the polymer were determined for the tensile bars by quantifying the surface energy for the different materials. This was done using a drop shape analyzer (KRÜSS GmbH). Water and diiodomethane were the liquids used to estimate the surface energy based on Fowkes' model.

The effects of the injection molding processing were determined by measuring the hot polymer melt contact angle on the mold surface.

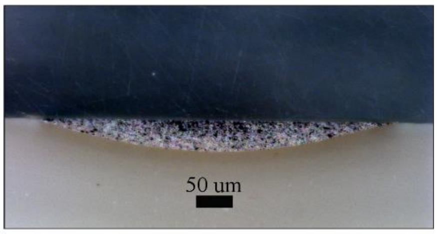

Fig. 5 Cross-section of the molded tensile bar

3.2 Mechanical Characterization

The mechanical properties of parts with and without the embedded ink were evaluated for the Type 1 tensile bar samples. Ten samples of the base ABS and five samples of the proposed process chain were tested. Tensile testing (Instron®, 5966) was performed at room temperature and in accordance with ASTM D638. A load cell of 50kN was used, and Young's modulus was determined as the ratio of stress at .2% strain.

Peeling tests in accordance with ISO 2409:2013 was performed to further evaluate the adhesion between the polymer and the printed ink traces using a pressure sensitive adhesive tape to remove the loose ink. The average dimensions of the ink traces on the tensile bar parts were determined to be a height of 200 µm, a width of 2 mm, and a length of 6 mm.

4. Results and discussion

4.1 Surface energy

Surface energy is a useful parameter as it can indirectly measure the adhesion between different materials [12]. The experimental trials showed that the mold surface energy increased by reducing surface roughness. Additionally, polishing the mold surface presented a surface that had a much greater polar affinity than an unpolished surface (9% contribution to 2% contribution). Additionally, the surface energy of the polished mold surface is greater than the surface energy of the sintered ink (37.5 ± 6.5 mJ/m^2 to 32.8 ± 3.8 mJ/m^2). Fig. 6 shows the resulting surface energy values of each of the surfaces. This figure shows that pre-treatment of the mold is necessary to release the printed ink traces from the mold and embed them within the plastic part.

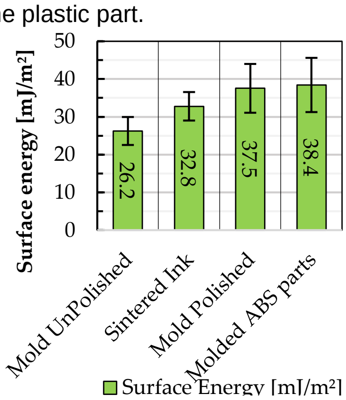

Fig. 6 Surface energy of each surface

4.2 Mechanical integrity and interface strength

The mechanical strength of the parts was obtained from Young's modulus, and the ultimate tensile strength (UTS). Figure 7 shows the average Young's modulus and the average UTS of parts with and without the embedded ink. The results suggest that the printed ink could potentially act as a reinforcement and thus increase the part's stiffness. In terms of the UTS, there is no significant difference between the parts with ink traces and the parts without. The average UTS of the pure ABS parts being 43.1 MPa, and the average UTS of the embedded parts was 43.2 MPa. These results suggest that the inclusion of the ink traces does not negatively impact the mechanical performance of the parts. However, due to the limited number of tested samples, further testing is required.

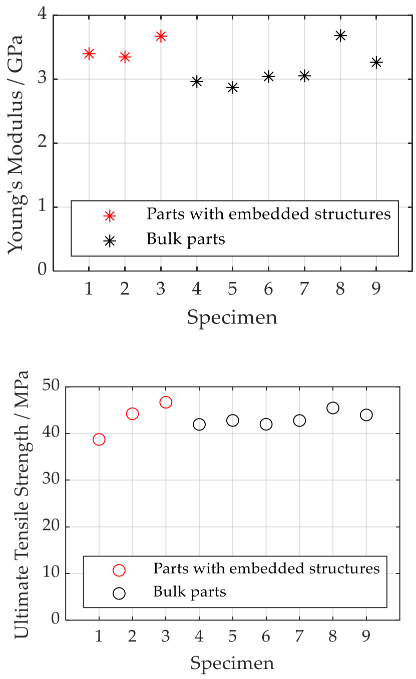

Fig. 7 UTS and Young's Modulus results

A peel test is a way of evaluating the adhesion of the polymer/ink interface. These tests were conducted on traces at different locations to determine the effects of injection pressure on interfacial strength. As shown in Figure 8, the peel tests resulted in strong adhesion, and no noticeable loss of any ink from the plastic substrate. These results suggest good adhesion between the polymer and the ink, and injection pressures having a negligible effect on the adhesion.

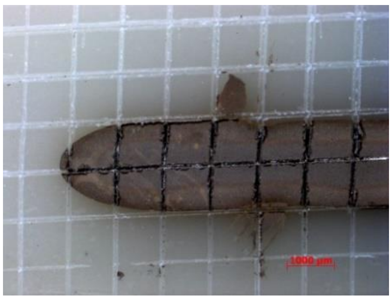

Fig. 8 peel test results

3.4 Effects of surface roughness

Real-world applications of printed electronics are highly limited by the roughness of the printed structures, and low wear resistance. As seen in Table 2, the surface roughness was evaluated for different surfaces involved within the process (printed ink (a), coating (b), polished surface (c), plastic part (d), embedded ink (e)). The evaluation resulted in a significant difference in *Sa* and *Ssc.* The 3D printed ink surface was determined to have the highest *Sa* and *Ssc,* with these values being 35x and 115x larger than the polished mold surface values, respectively. However, the plastic part's surface is similar to the surface of the polished mold, and the ink surfaces embedded within the plastic part resulted in *Sa* values 4x lower than the printed ink surface.

The roughness of the ink was due to the conductive silver which, when sintered, display anisotropic surfaces. The method presented in this paper shows that the 3D printed traces, when embedded within the plastic part, get "flipped." This results in the rough surface of the printed trace to be within the plastic part, which favors interlocking with the polymer melt. Additionally, the flipping results in a smoother surface and better wear resistance.

Table 2
Sa and *Ssc* results of the different topographies.

Surface	**a**	**b**	**c**	**d**	**e**
Sa	1396	603	39	52	315
Ssc	1.15	0.1	0.01	0.02	0.19

4. Conclusions

This work shows a novel process to integrate printed electronics within injection molded parts. This process results in parts that have lower surface roughness, due to the flipping of the structures when transferred from the mold to the par. These parts also exhibit better or unchanged mechanical properties which are comparable to the properties of the base polymer resin. Furthermore, they exhibit good adhesion as evidenced by the peel test.
Current and future work will focus on using different part geometries and more complex ink designs, such as that seen on the round disk.

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