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Sensors embedded in surface coatings in injection moulding dies

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Abstract

This paper describes results from EU FP7 project IC2 and beyond using surface embedded in surface coatings in thermoplastics injection moulding dies. Sensors where fabricated on the surface of inserts on a bridge tool for injection moulding of a component using Direct Write Thermal Spray. The sensors were encapsulated in an Al_2O_3 layers for electrical insulation and wear resistance. The data from the sensors was used to calibrate the FEM sensors for calibration of FEM process simulation and optimisation of conformal cooling channels on the production tool.

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Keywords: Coating, Sensor, Injection moulding

1. Introduction

Any innovation, technological development and optimization of products and manufacturing where tools are used, are closely interlinked with innovations on the tooling as well as the product itself. The goal of the EU FP7 project 246172, Intelligent and Customized Tooling (IC2) was to combine Additive Manufacturing Technology, Surface embedded sensors, coating technologies and utilise these enabling technologies to novel competitive business models for tooling industry [1]. The project focused on tools for injection moulding.

1.1. Process monitoring and control of injection moulding

Pressure and temperature distributions within the mould cavities are some of the most critical parameters for injection moulding of thermoplastics components. Sensors embedded in the surfaces of the mould cavities can be a step towards including process data from the injection moulding tools. The signals from such sensors can be used to gain more process knowledge, which again can be used to calibrate FEM simulations, for in process control and data acquisition (SCADA) systems [1] and Cyber physical manufacturing systems [3], [4] (a.k.a. Industry 4.0). In-mould sensors are increasingly used and as Gao et. al. [5] writes: ”*miniaturized and self-contained process sensors capable of monitoring both pressure and temperature near or right at the mold cavity become highly attractive to the injection molding industry for improved manufacturing process control*”. The most common control strategies are however, still dependent on “*sensors installed outside of the mold to measure hydraulic pressure, screw position, and tie-bar extension”* [5]. The reason for this is both the cost of in-mould sensors and signal transmission wires as well as practical problems with placing sensors in the mould cavities and robust wire routing.

1.2. Data for optimising FEM simulations of injection moulding

Bridge tooling allows early stage pilot manufacturing and faster time-to-marked bringing a product to the market while the full performance tools are being produced and it might be beneficial to include sensors in the bridge tools. This enables process data acquisition in an early phase that can be used to confirm, adjust computer simulations [6] and to optimize the design of the full performance tools. Traditionally full performance tools have been massive blocks of steel sometimes with gun-drilled, straight, cooling channels. By the development of novel additive manufacturing technology, it is now possible to integrate conformal cooling and heating

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channels in the tool [7]. Together, these channels make up an internal temperature management system permitting drastically reduced cycle times and improved quality by de-creasing warping, avoids sink marks etc. To fully integrate and optimize the positioning of these channels in the tool design, there is need for high quality in-data to make accurate simulations of the moulding process. Sensors that are incorporated in a prototyping and piloting phase could deliver enhanced analysis capabilities on tool, process and product behaviour such as thermal/mechanical stress, friction properties and inlet issues and offers an enhancement to virtual and numerical based simulation models that are of essential importance in the product development phase to ensure capability and robustness of the manufacturing processes. In this paper we describe a method for embedding sensors in coating layers and applied this on injection moulding bridge tool.

1.3. Mould surfaces

The material and the surface properties of the cavities of the mould dramatically influence the surface properties of the final product. Limited lifetime and loss of product quality of injection moulded components are often associated with a continuous decay of the mould by various wear and corrosion mechanisms such as abrasion from die and filler components, corrosion from aggressive gases and/or micro "explosions" formed during the moulding process, build up of residues from the plastic material, and fretting corrosion in connection with adjacent closing surfaces. However, advanced surface coatings may improve the mould surface properties, increase the wear resistance and enhance the lifetime [8], [9]. The tribological surface coatings used in tooling industry covers different coating types that are used in different tooling applications [10]. Examples are: (i) self-lubricant low friction coatings such as Diamond-Like Carbon (DLC), (ii) CrN coatings on surface parts directly in contact with the polymers, or (iii) high-energy nitrogen or chromium ion implantation to provide superior non-stick properties and en-hanced corrosion resistance of selected areas.

2. Surface-embedded sensors

As described can coatings bring benefits such as wear re-sistance and less frictional forces to the injection moulding process. The aim in the IC2 FP7 project was to merge three non overlapping worlds: (1) Manufacturing of injection moulding tools using AMT for conformal cooling, (2) coat-ings of tool three dimensional surfaces using Chemical Vapour Deposition (CVD), Atomic Layer Deposition (ALD), Plasma Enhanced CVD, and Physical Vapour Deposition (PVD) and (3) fabrication of MEMS sensors and the wiring to these sensors embedded in the layers. Figure 1 and 2 shows embedded sensors where the sensors are applied between layers of electric insulators. The top coating will typically be a wear resistance coating such as Diamond Like Carbon (DLC).

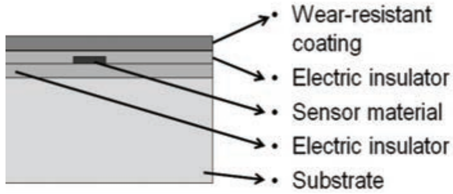

Fig. 1. Sensors embedded in coating layers

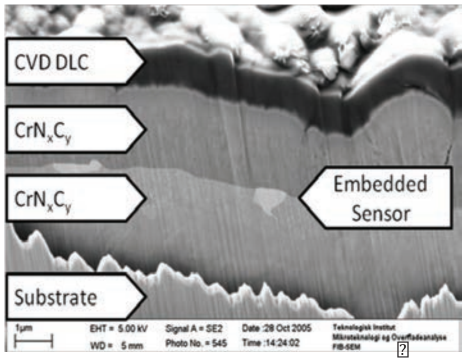

Fig. 2. Sensor embedded in coating layers

As the work in IC2 shows is one of the critical factor a pinhole-free electric insulator. Successful performance has been realized for Atomic Layer Deposition (ALD) combined with Physical Vapour Deposition (PVD) sputtering, and for sputtering combined with Chemical Vapour Deposition (CVD). The individual coating technologies are often not successful alone, and typically can a combination of ALD or CVD with PVD be the best solution due to a combination of line-of-sight limitations of PVD and the conformal characteristics of ALD/CVD based processes. To reduce the density of pinholes in the final film it is important to re-nucleate the film during deposition so the subsequent layer can cover defects in the coating [11],[12]. Furthermore was the task in IC2 to fabricate thin-film MEMS sensors on 3D (double curvature) surfaces rather than the con-ventional deposition of metal and isolation layers with photolithography processing techniques. These processes requires normally flat and smooth substrates e.g. silicon, quarts or glass wafers. Schonberg et al. [13] describes a method using a masking-and-coating approach to build a type T thermocouple thin film sensor, afterword covered by a wear resistant DLC coating. Schonberg et al. [14] reports from experiments in the IC2 project where K-type thermocouples were fabricated directly on the surface of a tool part using a Direct Write Thermal Spray process (DWTS) [15],[16]. DWTS enables additive manufacturing of multi-material patterns in 3D without any masking and is one out of may Direct Write technologies described by Hon et al. [17]. DWTS uses a miniaturised plasma gun on a robot arm. The process enables conformal fabrication of fine lines and structures suitable to build sensors and wires on the surface of mould cavities. The substrate will remain close to room temperature and a single layer can be down to 10 μm.

3. Industrial case study

The case study is focused on Plasto AS, a SME-company located in Åndalsnes in the west of Norway. The case product is a structural component; a sliding plate for a footrest complementary to a recliner chair (See Figure 3). The material used is PP 30 GF, a composite of polypropylene matrix with 30% long-fiber glass reinforcement. Injection temperature is 300°C, although friction raises the temperature even more during the injection of the polymer in the tool.

Fig. 3. Sliding plate for arm chair footrest

3.1. Bridge tool design and manufacturing

A bridge tool was designed in order to make a pilot production of the part. Figure 4 shows the tool design of the bridge tool with sets of removable tool inserts or pillars. Through this design it was easier to place sensors on critical positions such as in between the pillars and in the bottom of the crevices. The bridge tool had conventional cooling channels, i.e. no channels in the pillars.

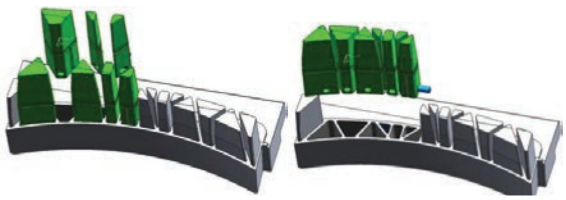

Figure 4. Bridge tool design with tool inserts / pillars

Two of the pillars where coated with Al2O3 for a nonconductive layer, and the sensor was built upon this layer using DWTS. The thermocouple sensors where built by combining Chromel and Alumel. The sensor where covered by a second Al2O3 layer, the last layer acting both as electric insulator and wear reticence. The embedded sensors where tested against a commercial thermocouple for reference, showing a deviation in the magnitude of 1°C between the sensor and the reference. A model of the tool pillar with the sensor is shown in Figure 5. Copper terminals for sensor wiring were placed on the end of the insert (shown by red dots). These have to be masked during the second nonconductive layer.

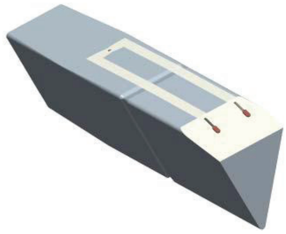

Fig. 5. Tool insert with Thermocouple sensor [14]

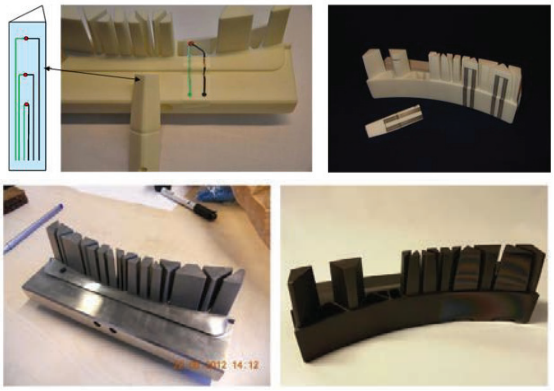

Fig. 6. Bridge tool for sliding plate footrest

Upper part of Figure 6 shows a 3D printed model of the bride tool and the bottom part the manufactured bridge tool. Both the bridge tool and the final production tool where made of tool steel in order to have equal properties. The bridge tool was made by milling and electrical discharge machining (EDM) processes. The surfaces exposed to the polymer was polished and then coated. Figure 7 shows the assembled tool before installing in the machine.

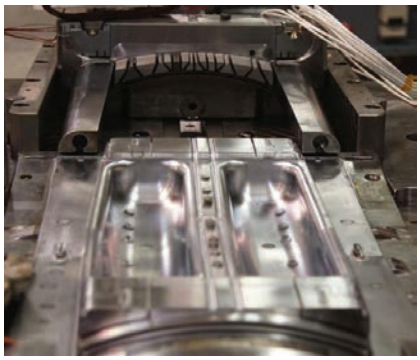

Fig. 7. Assembled bridge tool

3.2. Test run and sensor data collection

The bridge tool with the sensors was installed in an injection moulding production machine at Plasto AS and sensor data was collected. Figure 8 shows examples of the temperature readings, starting with a cold machine, Figure 9 at stable production. Pillar #6" shows temperature cycle on a location high up on an insert positioned deeper into the part cavity, Pillar #2 the position closer to the tool-end of the insert. The temperature of the Tool backside is where the insert is mounted to the slider and will be close to the internal cooling channels in the base of the bridge tool. Each "wave" on the curve indicates one production cycle and thus one component.

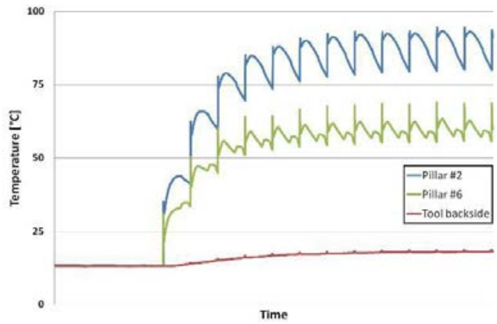

Fig. 8. Temperature readings from the sensors at process start-up

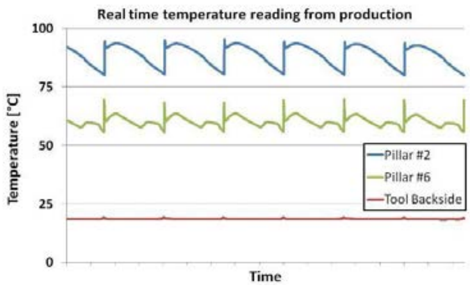

Fig. 9. Temperature reading from the sensors at stable production

Some interesting observation can be noted: a steady temperature is reached after approx. 10 cycles and the max temperature measured is less than 100 °C (in spite of 300 °C on the injected polymer. The reason for the low temperature is the instant solidification of the polymer – and the low heat conductivity of the solid polymer. The curve shows a peak at the beginning of the cycle when the hot liquid polymer hits the surface. The before mentioned solidification is the reason for the sudden drop after the peak, and then the temperature rises again due to the overall heating of the metal structure of the mould. A change in temperature is also noticeable at the ejection point.

3.3. Design of the production tool with conformal cooling

Moldex3D simulation software was selected for modelling of the injection molding process for designing a production tool with otimised conformal cooling channels and tool geometry. This software features the capability to place simulated sensors in the tool during the simulations. The output from the simulated sensors during simulation runs, was compared to the measurements from the test series production of the bridge tool. The simulations has been calibrated by adjusting input parameters to the simulations until the output from the simulated sensors correlated to the output from the real sensors on the bridge tool. Figure 10 shows a 3D computer model of the conformal cooling channels, and Figure 11 shows a picture from the simulation model for optimisation of the conformal cooling channels.

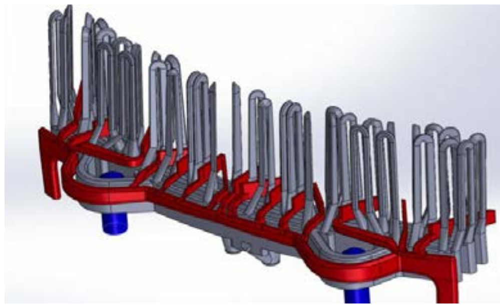

Fig. 10. Model of the channels for conformal cooling of production tool

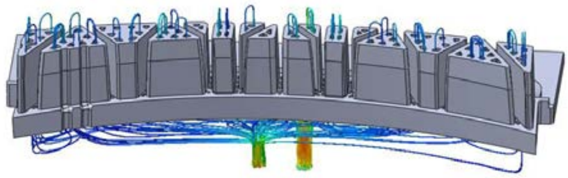

Fig. 11. Simulation of cooling of production tool

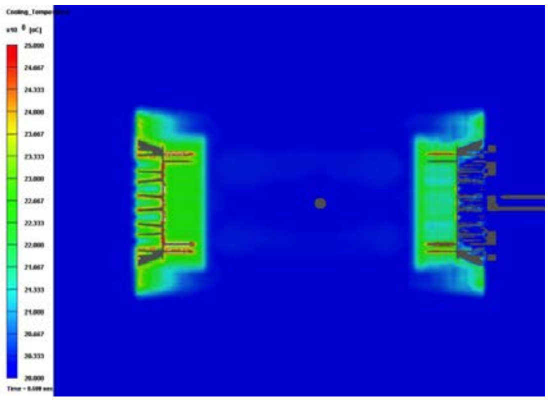

Fig. 12. Comparing cooling with and without Example of temperature distribution in Moldex3D simulation

Figure 12 shows a simulation of temperatures 0.5 seconds after polymer injection. The figure is a comparison between conformal and conventional cooling where the temperature without cooling (left) has been raised significantly while the temperature of the insert with conformal cooling (right) has hardly been affected.

4. Conclusions and further work

This paper describes methods for fabrication and installation of sensors on surfaces of injection moulding tools. A successful industry case where sensors on tool inserts on a bridge tool was used to calibrate the Moldex3D FEM model for an optimal design of the conformal cooling channels in the production tool. Plasto AS has used the production tool for more than 100 000 cycles and with estimated 30% faster cycle times compared to conventional tools. Due to the lack of an industrial viable signal processing, and the cost of sensors and sensors where not included in the standard production tool. This will, however, be the subject of further work. The use of sensor signals can be used for monitoring and process control, but would require a control strategy and a model. The research partners will investigate possible use of sensor fusion adding information from additional sensors inside or outside of the tool cavities, and perhaps use artificial neural network approach for signal processing and decision support. Furthermore will surface embedded sensors open new potentials for more advanced heat management of tools with dual or multiple channels for conformal heating and cooling. This can for example be used to accomplish both high quality surfaces and short cycle time, which requires solving the challenge of having a hot surface on the cavities at the instant of polymer injection, and still fast cooling of the whole work piece. In addition can further work include assessment of the effectiveness of surface embedded sensors related to other measuring strategies such as infrared cameras.

5. Acknowledgements

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