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Presentation of a Novel Sensor Based on Acoustic Emission in Injection Molding

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ABSTRACT: Injection molding is the most important process to produce plastic parts. Because of increasing complexity of the plastic parts and the aim to reach zero-defect production it is a must to control the dynamic injection molding process. Therefore information from the inside of the mold, measured with sensors, is necessary. State of the art is to implement wired mold cavity pressure sensors as well as wired cavity temperature sensors. This article presents a novel wireless measurement setup which uses structure borne sound as transport medium. The sound is generated by an acoustic actor which is activated by the passing flow front at certain predetermined positions in the cavity (or cavities). Beside the mechanical setup of the sensor proof of concept measurements with a prototype setup are shown in this article. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 000: 000–000, 2012

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INTRODUCTION

Injection molding is the most important process to produce plastic parts. For the production of high quality parts a continuous process control is necessary. Therefore a bunch of sensors with the ability to detect different measurement parameters are necessary to realize closed-loop control systems. In Ref. 1, Chen et al. propose a three level classification for injection molding. The first level represents machine variables such as temperature of the barrel or maximum injection pressure. These variables are normally well and independently controlled with proper controllers and sensors in feedback loop.[1,2] Level two variables represent the process variables such as the melt temperature, melt pressure (at different positions) or melt front advancement. Level three variables describe the complex area of quality variables such as part weight, shrinkage and warpage or optical defects.[1]

In this article, the focus of the work is on the level two variables and especially on a new method of measuring process parameters. Nowadays nearly all commercially available in-mold sensors are pressure or temperature sensors.[3] The temperature and the pressure sensors are used for example to control the instant of time to switch over the injection machine from filling to packing.[4] Cavity wall temperature sensors have received a special interest due to their small size, low cost, and durability compared to cavity pressure transducers.[4] One advantage of cavity pressure sensors is that they could be used to inline determining quality of the produced part.[1] The pressure influences for example part weight, thickness, and other dimensional features like shrinkage and warpage.[5,6]

There are some other sensor types, like infrared- or ultrasonic sensors but they are mainly used for research work only.[7–9] Furthermore there is current effort to develop new sensors, which are able to measure more accurately and to analyze a complete set of process states at once.[10]

What all these sensors have in common is that they are wired sensors. This involves drilling cable channels to embed the sensor head in the cavity. With increasing complexity of part geometries big effort has to be expended to implement the necessary components in the cavity (ejector pins, core traction, sensors, venting, etc.).[11]

So, there is a lot of current effort developing new wireless sensor concepts. The advantage is to need less structural modifications to implement several in-mold sensors.[12,13] The problem of energizing the sensor in the mold is one of the biggest challenges. In[12,14] a self-energized dual parameter sensor is presented. The sensor is able to measure pressure and temperature

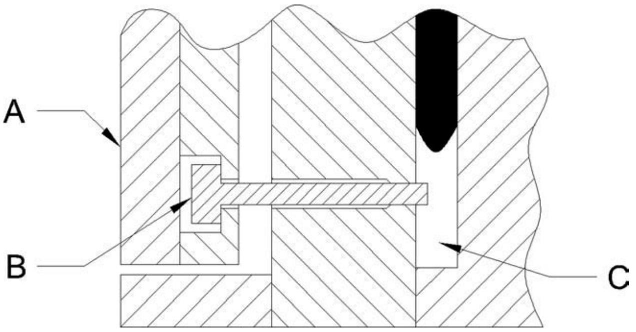

Figure 1. Sketch of a possible sensor implementation (polymer melt just before reaching the acoustic pin).

at the sensor position and to transmit the measured values through ultrasonic pulses. The energy is gained from the polymer melt and converted with a piezo stack. At the outside of the mold an ultrasound receiver is placed to receive the data.

In this article, a new wireless sensor concept for injection molding and proof of concept measurements are presented where no electronic parts are necessary in the surrounding of the cavity.

EXPERIMENTAL

Sensor Principle

The idea of this novel sensor concept is to transport a melt induced signal without a cable to an acoustic sensor, which is positioned at the outside of the mold. Therefore the energy of the melt is used to generate the signal in form of mechanical vibration. The first implementation uses a movable pin dedicated for sound generation, which is accelerated by the pressure in the melt and impinges on an object called acoustic element. This acoustic element gets induced and generates oscillations at its resonant frequency, which can be detected by an acceleration/vibration sensor placed on the outer surface of the injection mold. In the following, the unit consisting of a movable pin and an acoustic element is called acoustic device.

The acceleration sensor also picks up noise generated by the injection molding machine and other sound sources. When the melt front passes the movable pin during the injection phase an additional distinctive sound is generated on purpose. The task of the electronic signal processing is to separate the impact sound from the other noise to determine the instant of time, when the melt front passes the acoustic device.

The requirement of the acoustic device is to produce a clear, sharp sound signal which reacts quickly when the melt flow front passes. In a second representation, a specifically designed ejector pin with an intended backlash at the holding point can be used to produce such a distinctive sound. In Figure 1 a sketch of such a movable ejector is shown, where A is the ejector plate, B the specifically designed movable ejector pin and C the cavity, which gets filled with polymer. In Figure 2 the melt has already overflowed the ejector pin, which thereby was pushed against the ejector plate and emitted a distinctive sound.

At the start of the injection cycle the ejector pin projects into the cavity with the same length as the tolerance at the holding position of the pin. Experiments have shown that the backlash has to be about 0.3 mm to generate a detectable sound. When the melt front reaches the pin it gets accelerated toward the ejector plate (that hereby has the function of the acoustic element) until it impinges upon it. This impact generates a characteristic sound, which propagates without the need of a cable to the acoustic sensor located at the outside of the mold. Because of the pressure level inside the melt, the movable ejector pin is pressed against the ejector plate after impinging and stays in this position. As a result, just a typical ejector pin mark on the part surface can be found.

After reaching the ejection temperature the part is ejected using all the ejector pins including the one used as the movable pin. When the ejector plate is pushed backward to the initial position the ejector pin stays in the front position and is ready for the next cycle.

At present cavity wall temperature sensors are often used to detect the melt front. Their advantage is a very fast response time when the melt front passes the sensor head. Figure 3 shows the cavity wall temperature signal for 90 injection molding cycle. The sensor head has a diameter of 1 mm and has responded within 0.01 s.[4]

Because of their fast response time they are often used to produce a trigger signal to switch from injection phase to the holding pressure phase. Furthermore they are applied for automatic balancing of runner systems. Consequently each cavity has to be equipped with at least one cavity wall temperature sensor to detect the differences in the filling time of each cavity.[15]

Because of its functionality, the novel sensor concept is able to compete with cavity wall temperature sensors which are solely used as a trigger. If the acoustic device is located at the same flow path position as the temperature wall sensor both sensors detect the melt front clearly at the same time (see chapter results for details). If the sensor is positioned close to the end of the flow path the signal of the sensor could be used to switch the machine from filling to packing phase. The optimal position of in-mold sensors is discussed in Ref. 16 as well as in Ref. 17.

Compared to cavity wall temperature sensors the novel sensor concept has some significant advantages, which are discussed in the following section.

The acoustic sensor with its sensitive electronic is placed at the outside surface of the mold. There the environmental conditions are much gentler than inside the mold. The pressure which is

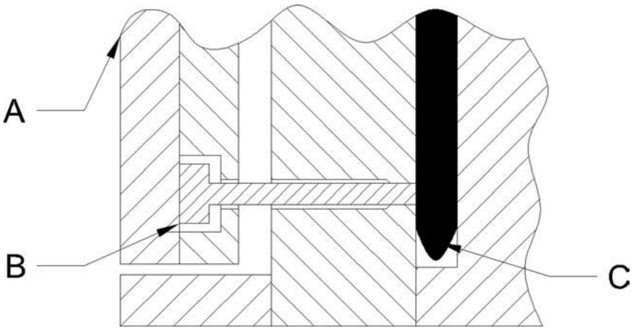

Figure 2. Polymer melt has activated acoustic pin.

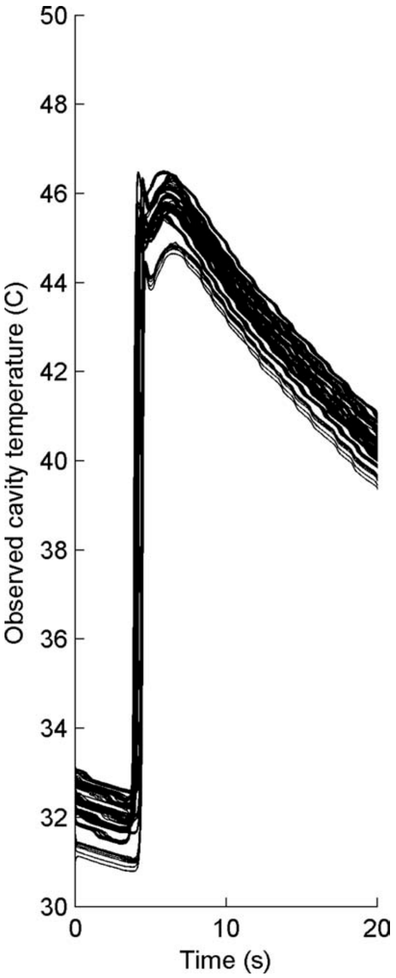

Figure 3. Wall cavity temperature signal for 90 injection molding cycles.[4]

loaded on the acoustic sensor is just atmospheric pressure. This is a huge improvement compared to the in mold built in sensors which are loaded with high cyclic pressures. Furthermore, the mold temperature at the outside of the mold is quite constant and at a moderate level. In addition the polymer melt is not in direct contact with the sensor which avoids abrasion. Each of these aspects increases sensor lifetime.

One of the biggest advantages of the sensor concept is that just one acoustic sensor with one evaluation unit is needed independent from the number of installed acoustic devices in the cavity or cavities. This reduces costs especially at higher cavity numbers. Another cost reduction fact is, that the acoustic device just consists of simple mechanic parts (like ejector pins). The durability of these parts, for example ejector pin, is proved by their use over years in nearly all injection molds.

Concerning the installation place the novel sensor concept has again advantages over other sensor types. No extra space for the acoustic device is needed because existing ejection pins can be adapted. When building new injection molds, no additional space and drilling for in mold sensor cables are needed. This reduces complexity in the construction phase and costs when building the new mold.

Another profit of the new concept is that due to the outside position of the acoustic sensor a change due to a failure is easy to perform. No disassembling of the mold is necessary to reach the sensor parts. In addition clamping and therefore destroying sensor cables during maintenance is impossible due to omission of them.

Prototype Configuration

For the research work a highly modular injection mold was constructed. The injection mold has two fully symmetric cavities which form oblong plates with ribs and breakthroughs. The parts are gated by a hot runner system with valve nozzles built by Guenther hot runner technology (Germany). The mold is able to carry two acoustic devices of versatile design. In addition the acoustic device could be replaced by a blank element. As a result the acoustic device can be “activated” or “deactivated” separately for each cavity. In Figure 4 a section view of the acoustic device (prototype for research work) used for the measurements is shown. The device consists of a movable pin which is pushed into the cavity by a spring. This ensures the correct pin position at the begin of a new injection cycle. The spring rate is very low to damp the accelerating pin as less as possible but strong enough to ensure it is not pushed by compressed air in front of the melt. The acoustic element is fixed by four screws which transfer the vibration into a mounting frame and further into the mold. For the first results a simple u-shaped sound item was used which has a calculated eigen-frequency of about 12,300 Hz. This result was calculated with Autodesk Inventor Professional 2011. The calculated result was verified by measurements which resulted in an eigen-frequency of about 11,200 Hz.

On the opposite cavity wall side of the position where the acoustic device is placed a cavity wall temperature sensor 4009b by Priamus System Technologies AG (Switzerland) with a sensor head diameter of 0.6 mm was placed. This allows comparing and verifying the gained signal information from the acoustic device with the signal gained by the cavity wall temperature sensor. The mold layout is shown in Figure 5.

The measurements were performed on an electric injection molding machine manufactured by Arburg Gmbh + Co KG (Germany) labeled Arburg allrounder 470A-1000 alldrive. In Table I a summary of the process parameters is shown. For the

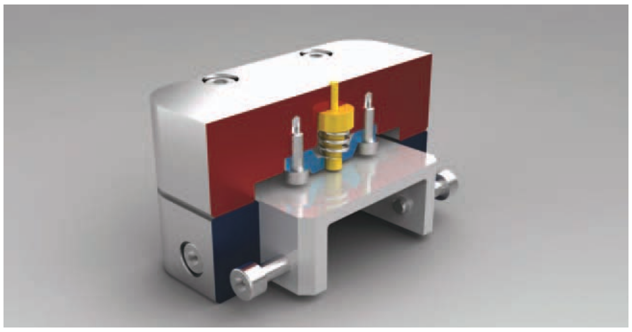

Figure 4. Section view of acoustic device. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

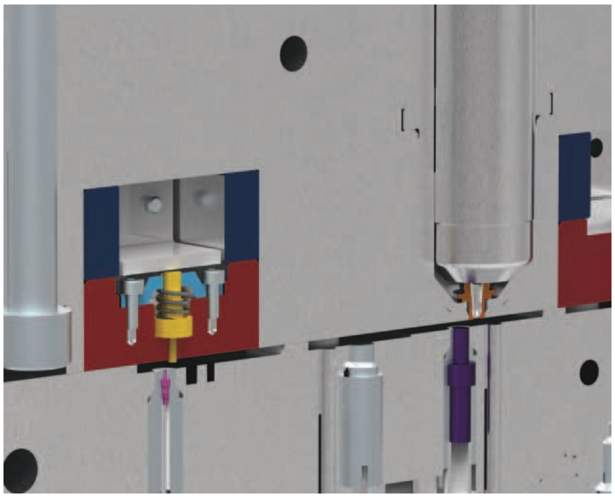

Figure 5. Mold layout in section view of one cavity. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

measurement a polypropylene (C-7069-100A) by Dow (Switzerland) was used.

The data is logged by a X20CP1486 programmable logic controller by Bernecker + Rainer Industrie-Elektronik Ges.m.b.H. (Austria). The cavity wall temperature signal is recorded with a frequency of 5000 Hz. The acoustic signal is recorded with a sampling frequency of 25,000 Hz. For the calculations and the visualization of the acoustic signal an envelope curve is calculated which is explained next.

Because the acoustic element causes a clear and distinct signal, the analysis can be done on the envelope, which requires much less computation effort than directly processing the acoustic input. After passing the analog/digital converter (ADC), the signal stream is subjected to a high-pass filter to remove low-frequency components, for example noise originated by machine components or an amplifier bias voltage. After this, the signal is rectified and the envelope is generated. Rectification is carried out simply by taking the absolute value. The envelope follows the signal immediately when rising, but decays slowly with a certain time constant. Figure 6 displays the original signal together with the resulting envelope.

The desired result is the instant of time when the melt reached the acoustic device which then generated the distinctive sound. With the envelope method this time could be calculated with minimal computation effort. This results also in loss of information, for instance when using multiple acoustic devices with different eigen-frequencies. With the method of the envelope it is just possible to detect the distinctive sound but it is not directly possible to assign it to a certain acoustic device. If one is interested which acoustic device generated the sound other methods such as bandpass filters, Short-time Fourier Transform (STFT) or Wavelets are appropriate methods and will be discussed in a further paper.

Table I. Summary of Process Parameters

	Value
Nozzle temperature (°C)	220
Mold temperature (°C)	40
Injection time (s)	1.05
Injection rate (cm^3 s^{-1})	60
Switch over method	Volumetric

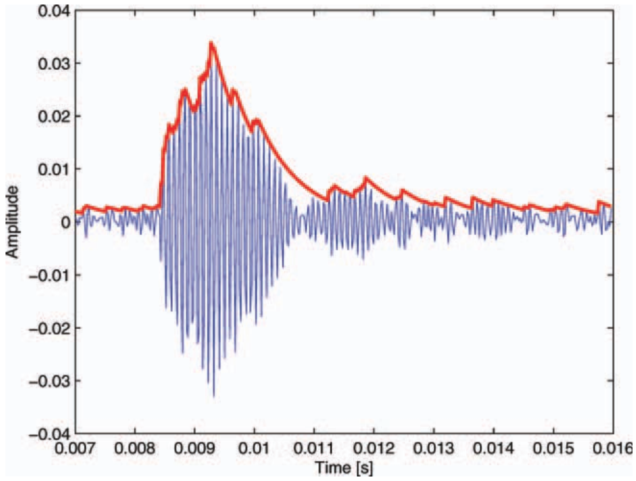

Figure 6. Actuator time signal and its envelope. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

After data recording, the temperature signal was smoothed by a moving average algorithm and the acoustic data was filtered with a high pass frequency filter. All the post data manipulation was carried out in OriginPro 8.6.

The existence of a spike caused by the acoustic actuator can be recognized applying the following criteria to the envelope: The first criterion is the amplitude, which has to exceed a certain limit, the second characteristic is the attack slope of the peak, and the third criterion is a minimum rectangle area that must fit under the curve. When these three conditions fire within the expected time range, an event is triggered.

RESULTS AND DISCUSSION

The measurements presented in this article have the purpose to verify the idea of the novel sensor concept. A series of measurements with three different configurations of the acoustic devices implemented in the mold was performed where the signal detected by the acoustic sensor and the temperature signals were recorded over time. From each series only one typical measurement is shown in this article. Each record was evaluated, according to the mold configuration, to test whether the signal detected by the acoustic sensor delivers the same information as the cavity wall temperature sensor. The information should yield the instant of time when the melt front reached the sensor position. The goal is a temporal match of information gained by the independent sensor systems.

The first series was performed with one acoustic device implemented in the mold. While injecting the polymer, it is expected, that at the time when the cavity wall temperature sensor detects an increase in the sensor head temperature, the acoustic device

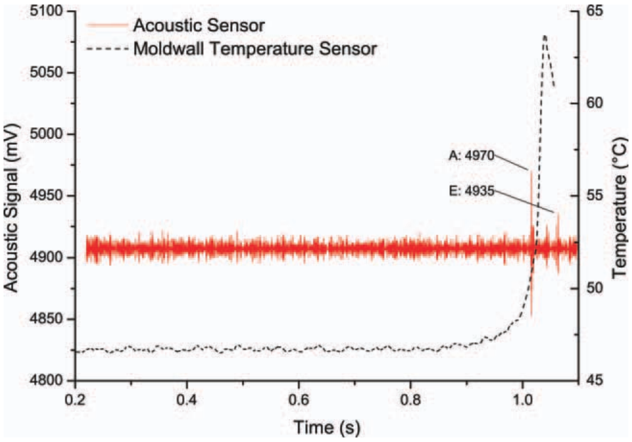

Figure 7. Evaluation of the recorded signals (acoustic and cavity wall temperature) with one implemented acoustic device. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

generates the expected distinctive sound. This event should occur, according to the injection rate and the sensor position, at about one second after start of injection. Figure 7 shows the recorded acoustic signal (solid Line) as well as the temperature signal (dashed line). When looking at the temperature signal it is clear, that the polymer melt reached the sensor position at about 1.0 s after the injection phase had started. It is quite difficult to give an exact instant of time when the melt reached the temperature sensor. The manufacturer of the cavity wall temperature sensor specifies a response time of 3 ms.[18] This time period does not consider effects like air heating like it happens at the diesel effect. Because of the fact, the sensor is positioned close to the end of the flow path, the polymer compresses the trapped air which leads to a temperature rise of the air. This may explain the slight temperature rise at about 0.9 s which afterward leads to steep temperature increase.

Regarding the acoustic signal, a ground noise level can be seen. At the point of 1.01 s a huge peak (marked with A) with a magnitude of 4970 mV (amplitude of about 60 mV) can be seen. This peak is generated by the acoustic device, which is verified using the blank acoustic device in the measurements described afterward. Comparing the time of the occurrence of this Peak A with the results from the temperature sensor proves a good match between the signals. In addition a peak marked with E occurs in the acoustic signal. With a magnitude of 4935 mV (amplitude of about 30 mV) it is obviously smaller than the Peak A. This peak appears throughout the whole measurement series which were performed. It is not known which part of the injection mold or the injection molding machine is the source of this sound. Because of its reliable occurrence with relatively low amplitude it does not affect the evaluation of the acoustic device, though. In addition, the signal E always appears after the filling phase and therefore has no influence on the evaluation of the acoustic signal.

The second series of measurements proves that Peak A was generated by the acoustic device. At this series the acoustic device was replaced by a blank, inactive element and the results are compared to those of the first series. Hence we expect with this configuration just ground noise at the point where the Peak A occurred before. Figure 8 shows again the temperature and the acoustic sound signal. The temperature signal is identical to that from series one (compare to Figure 7). The difference can be found in the acoustic signal. At the position where the Peak A was found in the previous measurement series now only ground noise is detected at the former Peak A moment. As a conclusion, it is obvious that the Peak A was generated by the former implemented acoustic device. Again the Peak E can be found in the signal. Its amplitude is of the same size as before (30 mV).

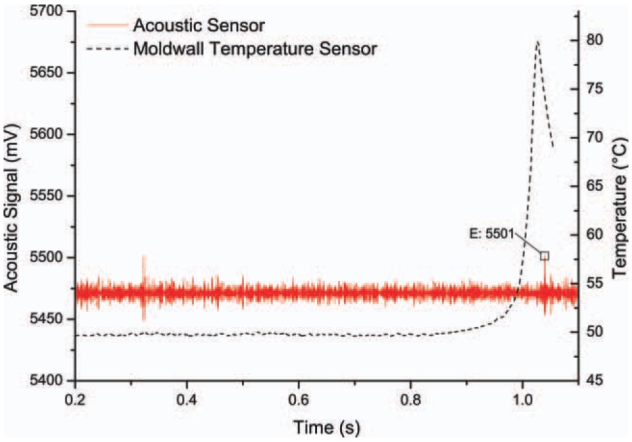

Figure 8. Evaluation of the recorded signals (acoustic and cavity wall temperature) with no implemented acoustic device. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Finally a third series of measurements with two implemented acoustic devices was performed. One acoustic device at each cavity but both placed at the same flow path position. At the opposite side of each acoustic device a wall cavity temperature sensor is installed. The results of these measurements are shown in Figure 9. Because of the second cavity an additional signal for the second cavity wall temperature sensor is shown but there is still just one acoustic signal. Regarding Figure 9 the temporally delayed increase of the temperature signal of the cavity wall temperature sensors indicate an unbalanced filling despite the fully symmetric configuration of the cavity as well as the symmetric hot runner system.

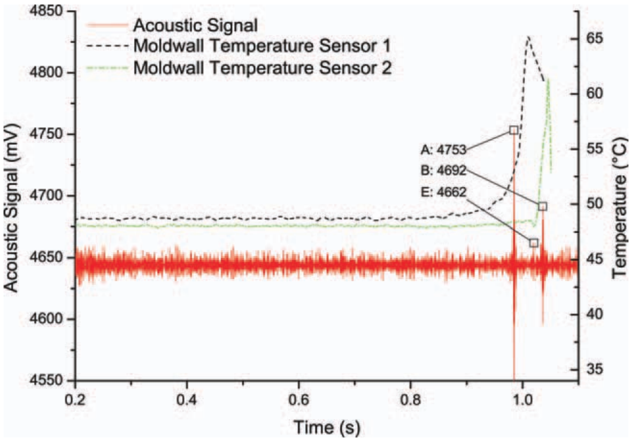

Figure 9. Evaluation of the recorded signals (acoustic and cavity wall temperature) with two implemented acoustic devices. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Thus the measured delay must be evoked by fabrication tolerances, slight temperature differences or deposits which influence the flow channel diameter in the hot runner system and the cavity itself. According to Ref. 11, temperature differences smaller than 1°C result in different flow behavior of the polymer. Evaluating the acoustic signal for this series, two clear peaks are expected to be found with the same time delay as seen at the signals of the temperature wall sensors. Figure 9 contains these two peaks marked with A and B. Both are obviously higher than the Peak E, which again appears with slightly lower amplitude than before (about 20 mV). The temporal match of each acoustic peak with the cavity wall temperature sensor signals is again very good. Peak A matches the instant of time of temperature rise of the corresponding cavity wall temperature sensor. Peak B also appears together with the rise of its corresponding temperature signal.

CONCLUSIONS

In this article a novel sensor concept for detecting the melt front position in injection molding is presented. Beside different possible mechanical setups measurements for proof of concept were carried out. The concept is based on the idea to generate a distinctive sound when melt front passes an acoustic device. The pressure in the melt front accelerates a movable pin which impinges on an acoustic element. This acoustic element oscillates at its resonant frequency which could be detected by an acceleration/vibration sensor placed on the outside of the injection mold. This setup and functionality leads to some huge advantages in construction effort as well as in lifetime.

To validate the functionality of the sensor concept three different measurement series were performed where the first series had one acoustic device implemented in the mold. It was shown, that a good temporal match is achieved between the signal information of the cavity wall temperature sensor, which is placed on the opposite cavity wall side of the acoustic device at the same flow path position for verification reasons, and the gained acoustic signal. To verify the assumption that the measured peak in the acoustic signal is generated by the implemented acoustic device, measurements with implemented blank acoustic elements were performed. In this measurement no peak was detected at the former point of the detected peak. Thus, it was proved that the implemented acoustic device is able to generate additional distinctive sound by passing of the melt front.

Furthermore, a series with two implemented acoustic devices was carried out. It was shown that two peaks were generated, each by one acoustic device, which again had a good temporal match with the signals generated by cavity wall temperature sensors.

The further work will be focused on an automatic robust detection of the peaks with one implemented acoustic device. Furthermore the functionality of the acoustic device as such will be examined in a deeper way by factorial designs (influence of injection speed, temperatures, viscosity or spring rate). Different acoustic elements with various resonant frequencies will be fabricated and examined. Moreover advanced signal processing methods, such as the Fourier Transformation or Wavelets, will be used to perform more accurate detection of the peaks. Furthermore, measurements with ejector pins instead of the prototype acoustic devices will be performed.

With the sensor concept it is also conceivable to measure the melt front velocity employing a higher number of special designed ejector pins. With the information when and which ejector pin generated a distinctive sound and the information about the geometry a velocity field could be calculated.

Moreover, using particular springs with predefined spring rates the sensor concept could measure that a certain pressure limit is reached in the melt at the position of the acoustic device.

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