It's the Inner Values that Count

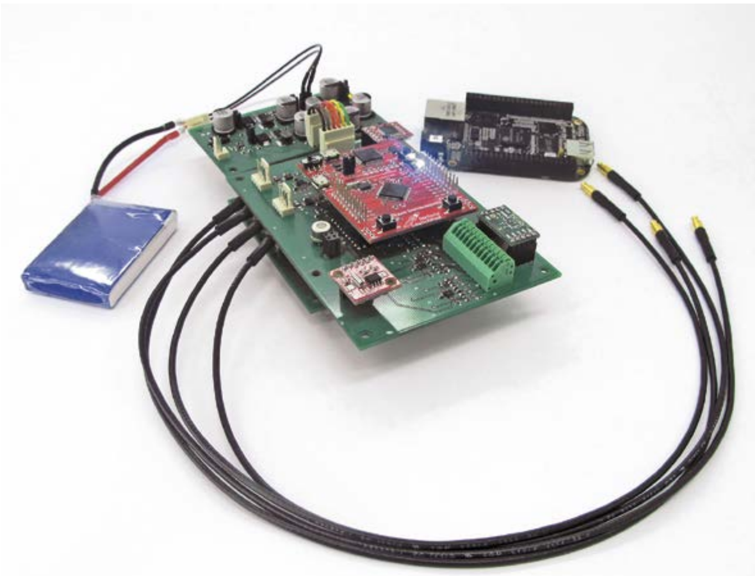
The Use of Embedded Diagnostic Systems in Injection Molds Benefits Mold-Makers and Users alike

"Industry 4.0" is a forward-looking project that seeks to interconnect production machines and associated processes completely, primarily with a view to boosting the efficiency of process optimization, procurement of operating equipment and planning of maintenance intervals and to conserve resources. If this vision is to be realized, new concepts will be needed for injection molding machines and their molds. In practical terms, this means computerizing injection molds along the lines of "Moldmaking 4.0".

Molds that fail to meet customer expectations on price and quality have certainly little chance of prevailing in the face of international competition. These might properly be deemed obligatory attributes. Optional attributes would then be service and reliability – but both factors are key to company competitiveness.

The industrial environment in which molds are used is headed for a radical transformation some time in the future. Already, innovative molds count as qualified production resources within validated processes and can no longer be considered in isolation as stand-alone components: they are integrated into highly complex manufacturing processes. This has implications for mold provision. First, attributes such as flexibility, precision and resource conservation will be priority requirements in the future. Second, the industry will expect molds to detect fluctuations and, by virtue of a self-learning process, to be capable of intervening in the production process.

Despite the presence of numerous sensors inside the mold to measure cavity pressures, melt contact temperatures and other process variables, the machine operator, i. e., the converter, is still expected to evaluate and exploit the data. This evaluation is generally performed at the machine, in master computer systems or by external third-party devices. For the purpose of implementing the idea of "Moldmaking 4.0" it makes more sense to get the mold to record and analyze sensor data and process variables and to decide on the necessary action for controlling any process fluctuations.



Hardware structure of an embedded diagnostic system (figures: University of Applied Sciences Schmalkalden)

Making Molds Intelligent

A research project at the Thuringia Center for Mechanical Engineering, Ilmenau, Germany, is currently developing an embedded diagnostic system (EDS) for the analysis and intelligent evaluation of the injection molding process. Code-named "Powermoulds", this is a joint project between the Laboratory of Applied Plastics Engineering in the Faculty of Mechanical Engineering and the "Embedded Diagnostic Systems" research group in the Faculty of Electrical and Electronic Engineering, both of which are part of the University of Applied Sciences in Schmalkalden, Germany.

The project is tasked with developing an intelligent overall system which is integrated or embedded into the mold. It will use mold sensors to record process parameters and perform the analog and digital signal conversion and processing. This will not only optimize production processes but also ensure high flexibility. Further objectives of the project are to detect wear and storage conditions. These readings are intended to support demand-driven planning of maintenance intervals and to ensure that molds are handled properly outside the confines of the production hall. »

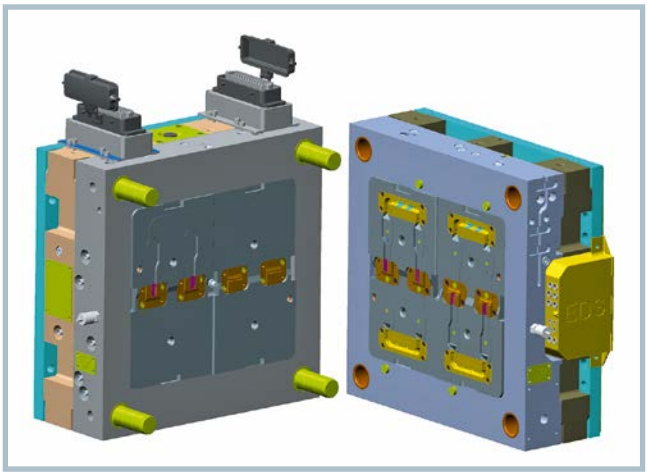


Fig. 1. 3-D CAD representation of the two-component tensile bar mold with the embedded diagnostic system (yellow, on the ejector side right)

These objectives are being pursued by integrating a total of 14 sensors into an injection mold. Installing sensors, electronics and intelligent analysis algorithms will lay the foundations for autonomous machine diagnostics. Currently, the project is focusing on recording the various process parameters and evaluating them off-line in different situations. Later, these results will be used to perform online evaluation and process feedback control based on the mold signals.

Modular Hardware Concept

The EDS is being developed around a 2C turntable mold (**Fig. 1**). The demonstrator parts are two-component tensile specimens with different abutment surfaces. A notable feature is that the sensors are drawn from standard components, a wide selection of which is available on the market. The sensors having been matched to the specification, the next step is to dimension the measuring electronics. A modular approach has been adopted here to facilitate adaptation to other injection molds. Thermal decoupling is ensured by building the EDS into a housing. An active cooling system avoids excessive temperature stress and guarantees that the measuring electronics work properly.

The measuring hardware which has been developed so far consists of

- four purpose-built charge amplifiers [1] for the piezoelectric cavity pressure sensors (type: 6001A, manufacturer: Priamus System Technologies AG, Schaffhausen, Switzerland),
- two purpose-built amplifiers for the force sensors (type: MK26 10 kN; manufacturer: ME-Meßsysteme, Hennigsdorf, Germany),
- four purpose-built amplifiers with AD converter for the melt contact temperature sensors (type: 4050A, manufacturer: Priamus) and mold wall temperature sensors (type: Z1295, manufacturer: Hasco Hasenclever GmbH + Co KG, Lüdenscheid, Germany),
- a specially designed power supply board (self-build),
- a microcontroller board (type: Tiva C Series TM4C123G LaunchPad [2]),
- a microprocessor board (type: BeagleBone Black),
- a micro-SD card module,
- an RTC (real time clock), and
- three sensors for monitoring the storage conditions (humidity, temperature and acceleration).

The sensor data are transmitted via the amplifiers to the microcontroller and are evaluated and stored in the microprocessor board (**Fig. 2**). The current hardware configuration of the embedded diagnostics system is designed as a handy package (**Title figure**).

Recording and Analysis of the Readings

The recording of the plethora of sensor signals requires a sophisticated timer concept. The idea here is to ensure that the readings of each sensor are recorded as fast as possible and logged synchronously [3]. All the peripheral system modules are initialized at start up. These include the amplifiers for the force sensors and the analog/digital converters for the thermocouples. All sensor signals are recorded at a sampling rate of 1 kHz, converted to digital values and transmitted. Scilab Software has been used to write several programs to display the data blocks for the offline evaluation. As regards development of the hardware, all the data are still being evaluated; when it comes to the actual implementation, down-sampling will be necessary, i. e., only the genuinely relevant parameters will be selected.

The sensor signals, e.g., the piezo-electric pressure signals, are transmitted as a stream of raw data via a serial interface and

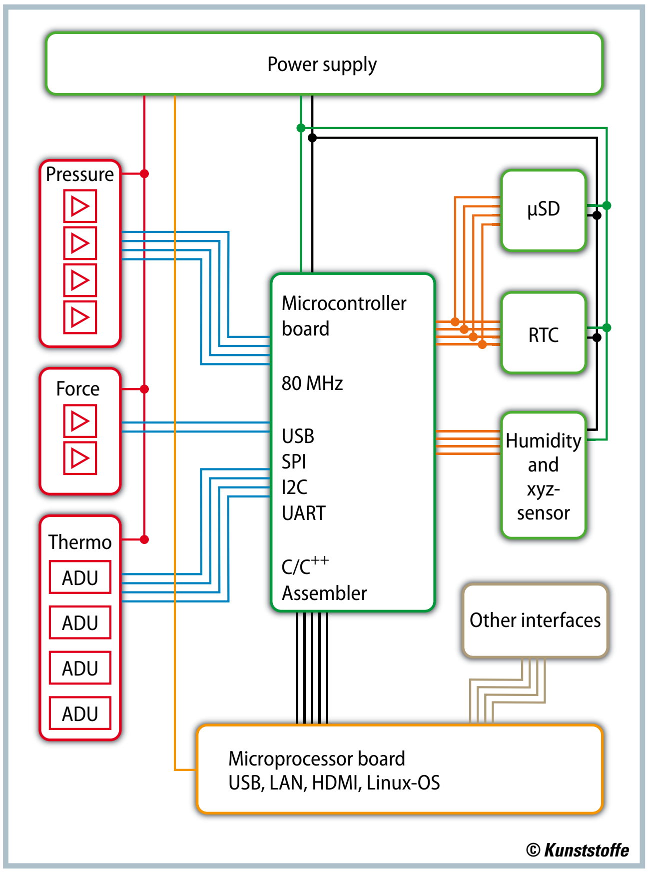


Fig. 2. Block diagram of the hardware components used. All sensor data converge via the measuring amplifier in the microcontroller board. A microprocessor board evaluates the readings and saves them

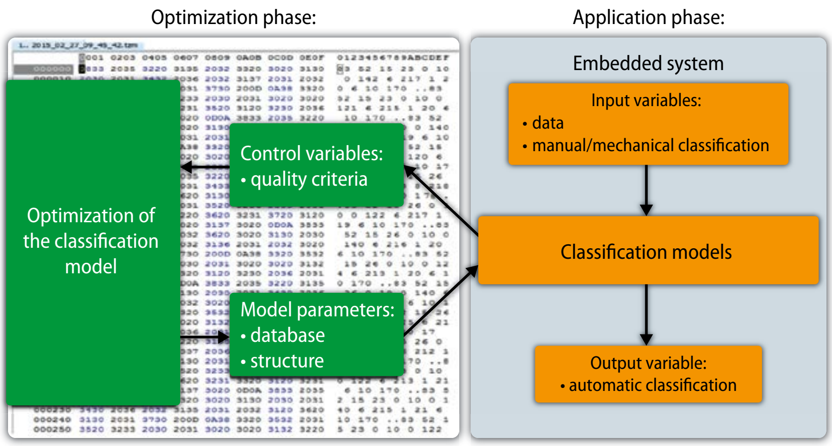


Fig. 3. Flowchart of the classification algorithm for autonomous determination of production quality. Inside the EDS, the readings are evaluated via classification models. The optimization phase reveals which model provides the most reliable information

saved as ASCII files. One advantage of transmitting raw data is that it keeps down the number of calculations performed by the microcontroller, and so ensures speedy forwarding of the sensor data to the evaluation unit. Furthermore, during later machine analysis, the raw data support direct extraction of information that is difficult or impossible for the machine operator to recognize.

Before the readings can be analyzed, the optimum process parameters need to be determined to serve as a reference. For complex injection molds, this is best accomplished with the aid of design of experiments (DoE), which entails performing a defined number of injection molding trials. Predetermined target variables help to determine the optimum process window, which thereafter serves as a reference. A further advantage of this approach is that it generates defects in the molded parts more or less randomly. These defects provide characteristics for autonomous classification by the machine – the classification algorithm (**Fig. 3**) can learn to distinguish between "good" and "bad" molded parts.

Testing the Functionality of Measuring Electronics and Evaluation Hardware

The input variables and the manual or machine classification provide information to form the basis of a rough classification model that automatically performs a "good" and "bad" classification as output variables. Optimization algorithms ensure that this rough model is self-optimizing during ongoing production. The machine operator, too, can adjust the software through automatic code generation and simple block diagrams in the Matlab and Simulink environment (**Fig. 4**).

The functionality of the purpose-built measuring-amplifier circuits was verified in an extensive experimental plan. Minitab16 QM software was used to devise a fractional factorial design comprising 36 variations of machine setting parameters. All variations were limited to the injection of the first component; the second component was processed under constant machine settings. Parameters varied were

- the injection speed,
- the hot runner temperature,

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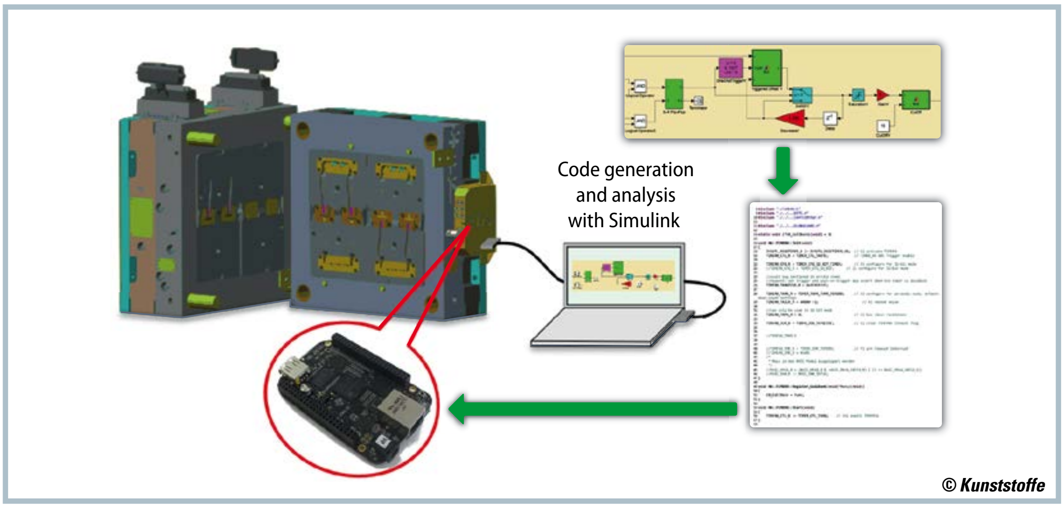

Fig. 4. The operator uses block diagrams to adapt the software to the hardware modules employed. This supports intuitive operation – in-depth programming skills are not necessary

- the temperature of the mold heating and cooling medium,
- the holding pressure level,
- the holding pressure time, and
- the residual cooling time.

The target parameter is maximum adhesive strength of the bond in the butt joint between the two plastic components. The material for both components in each case is a polypropylene (type: PPC 9760; manufacturer: Total Petrochemicals & Refining SA/NV, Brussels, Belgium). The second component is dyed with a masterbatch (type: 6301050 RAL 6037, 2% green; manufacturer: Masterbatch Winter GmbH, Mühlheim am Main, Germany).

The changeover point is set volumetrically. Viscosity fluctuations are not compensated for – these will be the subject of future investigations. The experimental design simultaneously serves to train the evaluation software. Due to the wide variation in process parameters, irregularities arise automatically in the process that are not readily apparent in the finished molded part. The embedded diagnostic system performs a sensor-based evaluation of the process parameters to establish if these irregularities can be made visible.

To date, the functionality of the purpose-built measuring amplifier has been confirmed. For comparison, parameter sets have been run and the cavity pressure and melt contact temperature sensors compared with the machine's own measuring amplifiers (type: 5060D; manufacturer: Priamus; and type: KIG3132-7; manufacturer: Kistler Instrumente AG, Winterthur, Switzerland).

The outcome of the injection molding DoE is, as expected, that the temperature of the temperature-control medium and the hot runner temperature exert the greatest influence on the adhesive strength between the tensile-rod components (**Fig. 5**). The influence of the two temperatures on the filling behavior reveals itself especially in test series 2 and 15: The curves for cavity pressure differ extensively from each other (**Fig. 6**). The readings of the temperature sensors can be used to draw conclusions about necessary countermeasures. If the readings move outside the defined process window during series production, the system provides feedback, enabling appropriate countermeasures to be taken.

This DoE model allows the process to be optimized for maximum attainable adhesive strength. The modeled optimum op-

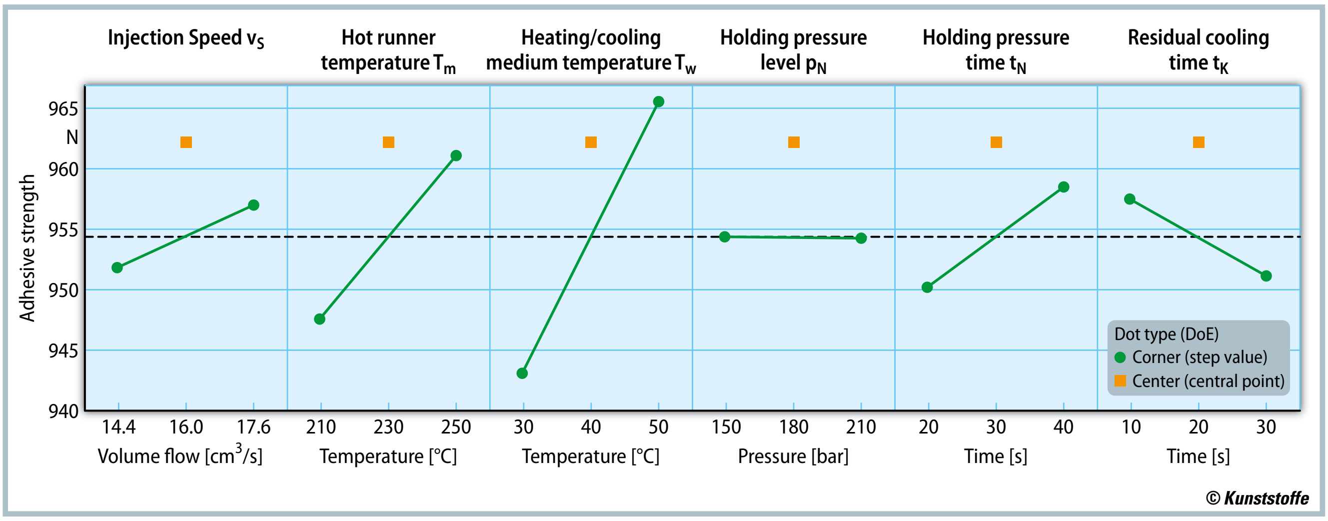

Fig. 5. Main effects chart for the target parameter adhesive strength of the two-component tensile rod. A knowledge of the most important influential factors supports targeted process optimization. The results are used for training the EDS classification algorithm

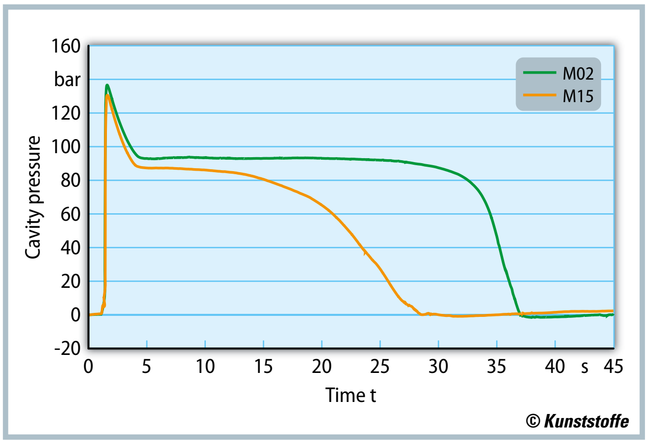

Fig. 6. Comparison of pressure curves within two series of measurements (2 and 15) of the experimental design. Different temperatures in the hot runner and temperature control medium yield different cavity pressure ratios, which the diagnostic system detects and feeds back

erating point is set and the embedded diagnostic system is trained. Simultaneously, the sensor readings are superposed to create a process window in which the target value can be reached.

Monitoring also takes place away from the production hall. Integrated sensors for humidity, temperature and acceleration detect and record storage conditions. Companies can use this information to investigate any increase in the frequency of cavity corrosion or mechanical damage.

Conclusion and Outlook

Embedded diagnostic systems create for the user a basis for sensing and recording important process parameters at source and, via the feedback provided by the diagnostic system, to run the process in the optimum operating window. For mold makers, this presents an opportunity to ship process data along with the mold. Users would thereby receive important information about operation of the mold and would be spared having to do this tedious work. At the same time, the mold would be protected from improper operation.

The EDS is also capable of saving and confirming product data, mold design data and maintenance intervals. This allows changes in product data and mold geometries to be directly captured and stored. Especially where designs are changed or molds are relocated to a new production site, this ensures that all the information is available and is up to date. Maintenance work is documentable and verifiable.

A later expansion stage of the EDS will be to connect an interface to the injection molding machine. This interface will then be used to intervene in and control the injection molding process, thus ensuring the long-term stability of the process.

Looking forward, this means: for the production mold, networked processes will become a real option through self-optimization, self-configuration, self-diagnosis and cognition. For the mold-making industry, it is a chance to develop new business areas that transcend the construction of injection molds. And for the user, these developments mean more rugged processes in a valid production environment. ■