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INLINE INFRARED THERMOGRAPHY APPLIED FOR QUALITY GATES AND FOR MOULD TEMPERATURE CONTROL IN THE INJECTION MOULDING PROCESS

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ABSTRACT

In injection molding processes, the precise control of the mold temperature distribution often is a crucial prerequisite for the quality of the final products. The demolding temperatures of molded parts are depending, among others, on the cooling time, the temperature distribution of the mold and injection process parameters like melt temperature and injection pressure.
For the control loop of the mold temperatures, established technologies use either the coolant-flow and -temperatures in the recirculation pipes or the mold temperatures, measured by sensors in the mold, as reference variables. Thus, only the average temperatures or some, by the selected position of the sensors predefined, spot temperatures can precisely be controlled.

A new approach to overcome those limitations is the use of infrared images of demolded parts to realize a closed loop temperature control. For complex technical parts with segmented mold-cooling systems, running at optimized cycle times and within small process windows, the inline use of surface temperature control can help to improve the product quality and increase the process stability.

Additionally the principle of measuring the part surface temperatures at the end of every molding-cycle and comparing them to the temperatures of e.g. approved parts enables the precise detection of thermal deviations and thus, applying temperature limits, the automatized rejection of faulty pieces.

Without the necessity for changes in the mold, the inline thermography can help to improve the quality, to keep cycle times short and to avoid scrap.
In the scope of a public funded research project, the application of inline thermography for the mold-temperature-control and for automatic quality gates in the injection molding processes was successfully developed and investigated.

1. STATE OF THE TECHNOLOGY

In injection molding processes, the mold temperature significantly influences the surface quality of the parts, the filling behavior and the cooling rate. The cooling rate of molded parts impacts among others the crystallization process of semi-crystalline materials and therewith the shrinkage behavior and the mechanical properties of the plastic parts [1].
For high quality articles produced at optimized cycle times, the cooling time must be kept as long as necessary and short as possible. To ensure stable production within the defined process window, the mold cooling must be precisely controlled to avoid disturbances caused e.g. by varying coolant-temperatures and –flow rates.

For closed loop mold temperature controls in industrial environments, many applications use the coolant temperature in the recirculation pipes and the coolant flow rate as reference variables. If such systems are installed for every cooling circuit and if their deviations are monitored (e.g. in case of clogging of pipes), a high reproducibility of the average mold temperatures can be ensured.
In some cases also mold temperature sensors are used to enable closed loop controls. For the functionality it is required that enough sensors are used and that their positions are located close to the critical segments of the mold. The risk of damage of the sensitive sensor connections and the complexity of localization and parameterization however limits the industrial usability.

For the quality control of complex parts CCD (charge-coupled device) camera sensors are applied to check the physical part dimensions and to detect short-shots. The availability of high resolution systems enables the design of very precise systems. Due to the poor reflection of dark colors and the impact of scattered light, often high efforts are needed to install and maintain the functionality of those devices.

2. INFRARED MEASUREMENT

Radiation pyrometers and infrared cameras are frequently used in numerous applications. In the recent years the decreasing costs of IR cameras opened a wide field of new applications. For many years IR cameras have been helpful to determine the surface temperatures of molded parts for research projects, for failure analysis and for mold optimization [2]. Now they are inexpensive and robust enough to be installed in a production environment and to be used for continuous process control [3].
An obvious approach to improve the process could be to measure the mold surface temperature and directly control it. But the accuracy of IR measurements directly on mold surfaces suffers from the relatively low emissivity of metals in the spectrum of standard IR bolometer arrays (polished steel e.g. emits only between 5% and 20% and reflects 80% to 95% of IR radiation in the wavelength between 8 μm and 12 μm).
The high and nearly constant emissivity of most plastic parts of around 95% is widely independent of the surface structure and of colors. Furthermore the relative low heat conductivity of plastic materials reduces the transient temperature changes after demolding. This allows quite accurate measurements of demolded articles. Due to the fact that the surface temperature of demolded parts is closely connected to the temperature of the mold, this approach uses IR images of articles to control the coolant flow settings and thus the mold temperature.

3. INLINE THERMOGRAPHY

Usually for every new mold the optimized production parameters, including mold-temperature-settings are determined and thereafter samples e.g. for approvals are molded. Thermal images of those demolded articles indicate the optimized mold temperature settings and may be used as a reference for series production. Figure 1 shows an example in the upper left image a).
The comparison between actual IR images, taken in every cycle of the running production (figure 1 b), and the reference IR images visualizes the difference shown in figure 1 c). The temperatures in c) are calculated for every pixel according to

$\Delta\vartheta c_{(i,k)} = \vartheta b_{(i,k)} - \vartheta a_{(i,k)}$. Blue color visualizes $\Delta\vartheta c_{(i,k)} < 0$, red shows $\Delta\vartheta c_{(i,k)} > 0$.

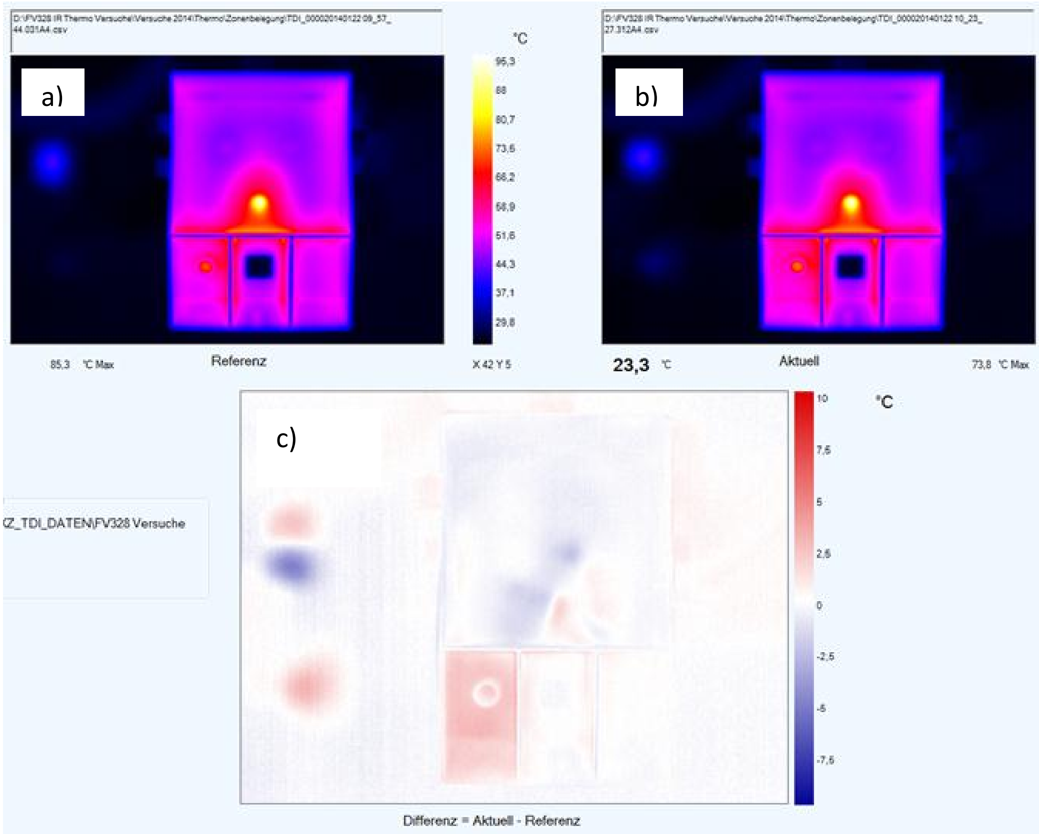

Figure 1: screenshot of temperature comparison

For the system setup, variations of the coolant flow in the circuits are applied to detect the area of influence of every circuit (Figure 2) and thus the position of the cooling circuits for the temperature control system.

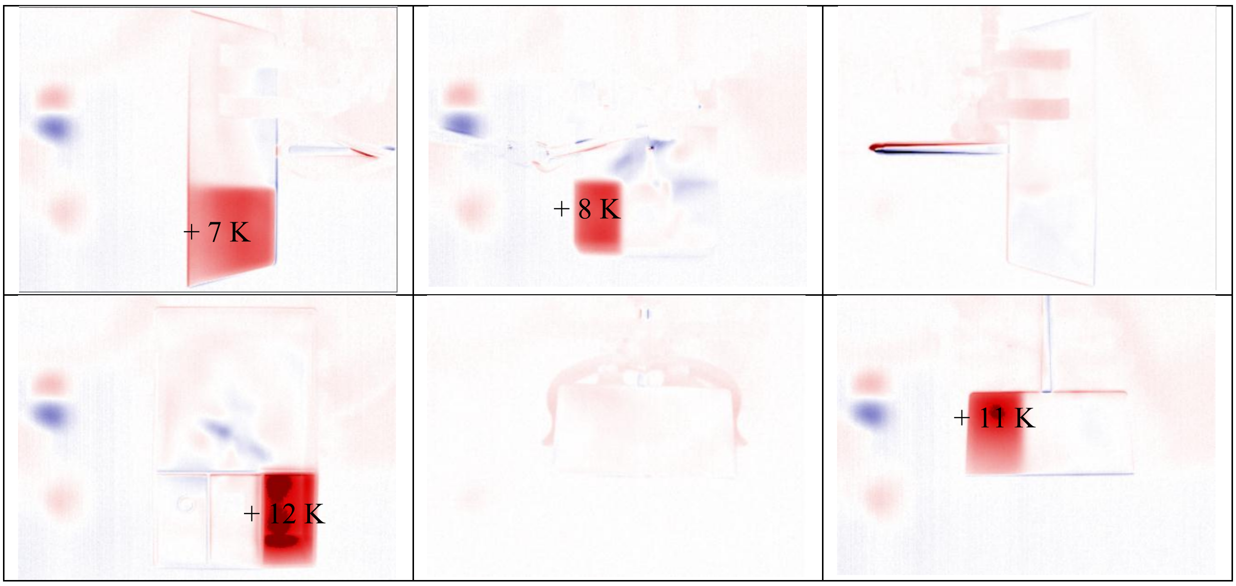

Figure 2: temperature differences when reducing the coolant flow of one segment show the areas of influence

4. EXPERIMENTAL SETUP

The part with the dimensions 160 mm * 100 mm * 50 mm was designed for the experiments as shown in Figure 3. The mold contains in total nine cooling segments (Figure 4) that were thermally insulated also at the nozzle side by partial gaps between each other. For the experiments, two circuits in segment 1 were connected in serial.
An injection molding machine TM 1300 from Battenfeld in combination with a handling from Wittmann was used to produce the samples. The coolant flow was controlled by a set of eight on-off valves in combination with specially designed temperature control units from Autotherm. The IR Data acquisition was executed with the camera model TIM 400 from Micro Epsilon.

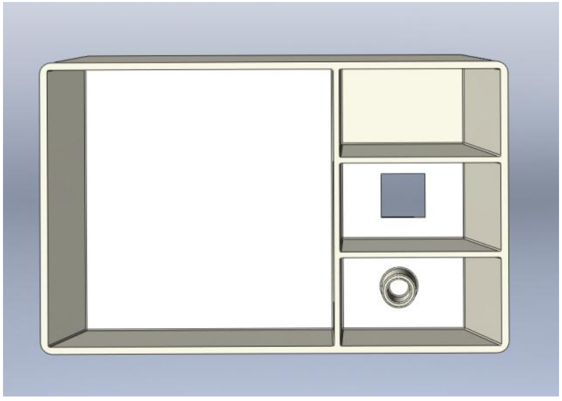

Figure 3: plastic part design

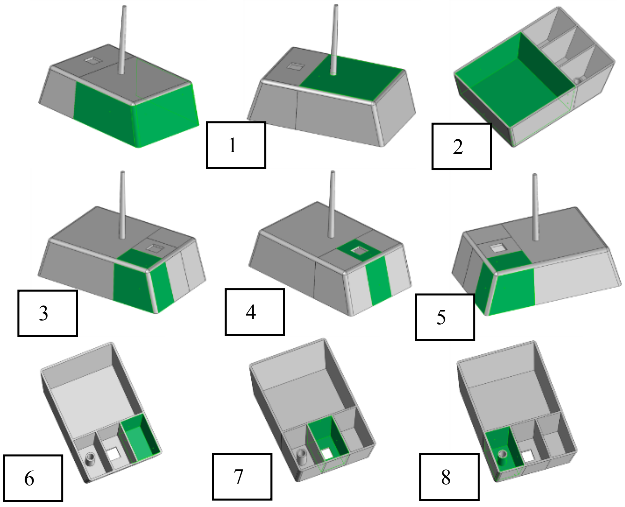

Figure 4: cooling segments with zones 1 to 8

In each molding cycle, the part was presented by the handling system in 6 aspects in front of the IR camera as shown in Figure 5.

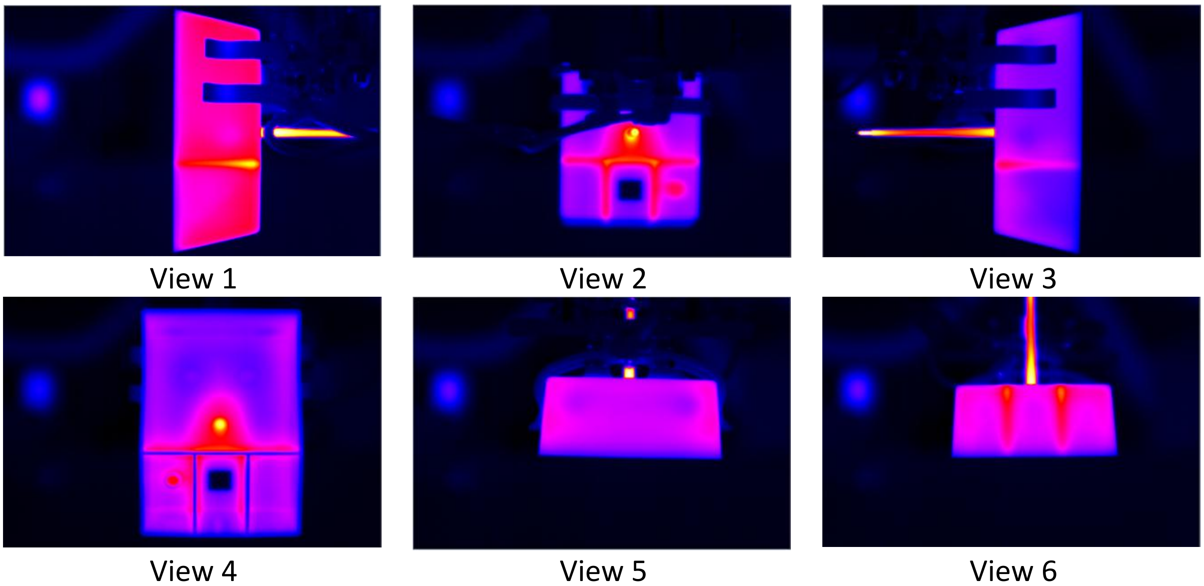

Figure 5: aspects for the IR measurement

5. TEMPERATURE CONTROL

A slightly modified proportional–integral–derivative (PID) control algorithm is used to calculate the output for the coolant flow variable $y(t)$:

$$y(t) = K_l - K_{PR}\left(e(t) + \frac{1}{T_N}\int_0^t e(\tau)d\tau + T_D\frac{d}{dt}e(t)\right) \qquad (1)$$

Here K_l is a constant for a predefined coolant flow, K_{PR} the total gain, T_N the integral time, T_D the derivative time and $e(t)$ the control deviation. The control loop is visualized in Figure 6.

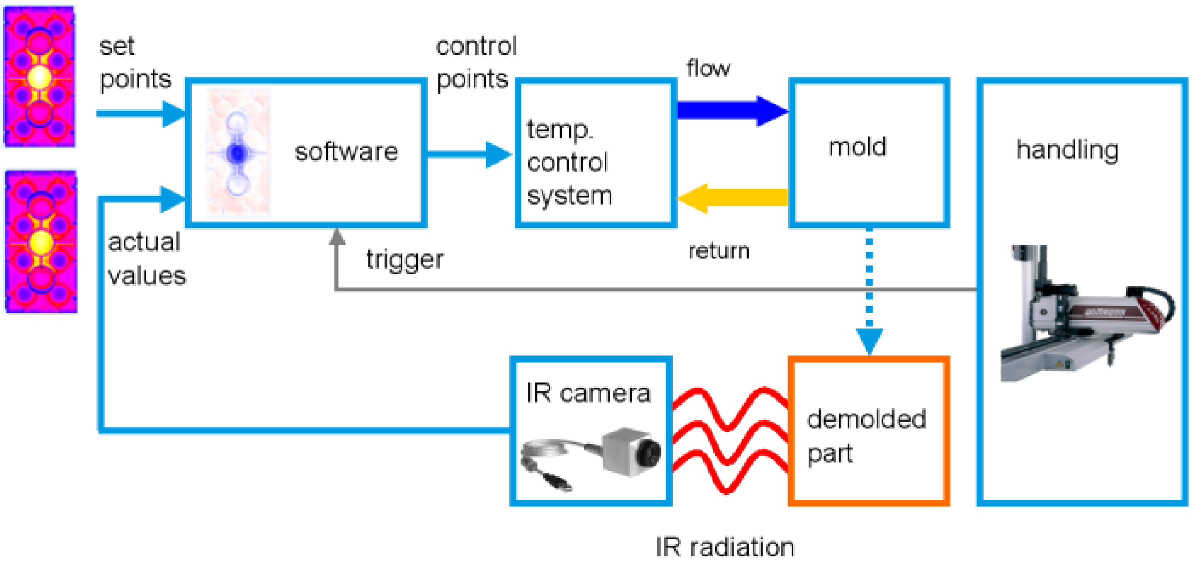

Figure 6 : schematic diagram of the control loop

For the closed loop control of the mold temperature settings switching valves are opened and closed during the molding cycle according the calculated coolant flow for every segment.

The control path (mold and temperature control system) can be described as P-T1-Tt element, characterized by its step response $x_a(t)$ with the gain K_{PS}, the step-signal x_{e0}, the dead time T_t and the time constant T_S.

$$x_a(t) = 0 \; for \; t < T_t \; and \; x_a(t) = K_{PS} \cdot x_{e0}\left(1 - e^{-\frac{t-T_t}{T_S}}\right) for \; t \geq T_t \qquad (2)$$

Step responses (example see Figure 7) were measured by starting the injection molding process with an opened loop. Due to the relatively small time constants of this step response, this operating mode is more critical for the controller than e.g. temperature changes of the coolant or slowly reduced coolant flow. The applied principle of sampling control requires, according to the Nyquist-Shannon sampling theorem, that the sample-rate (which is in this case limited to 1 sample / molding cycle) is equal or higher than twice the frequency of the measured signal. This can become critical, if the time constants of the control paths get small due to mold segments with low mass. Adding a constant cooling K_l in the PI algorithm helps to solve this problem for small T_S by increasing the damping of the control path.

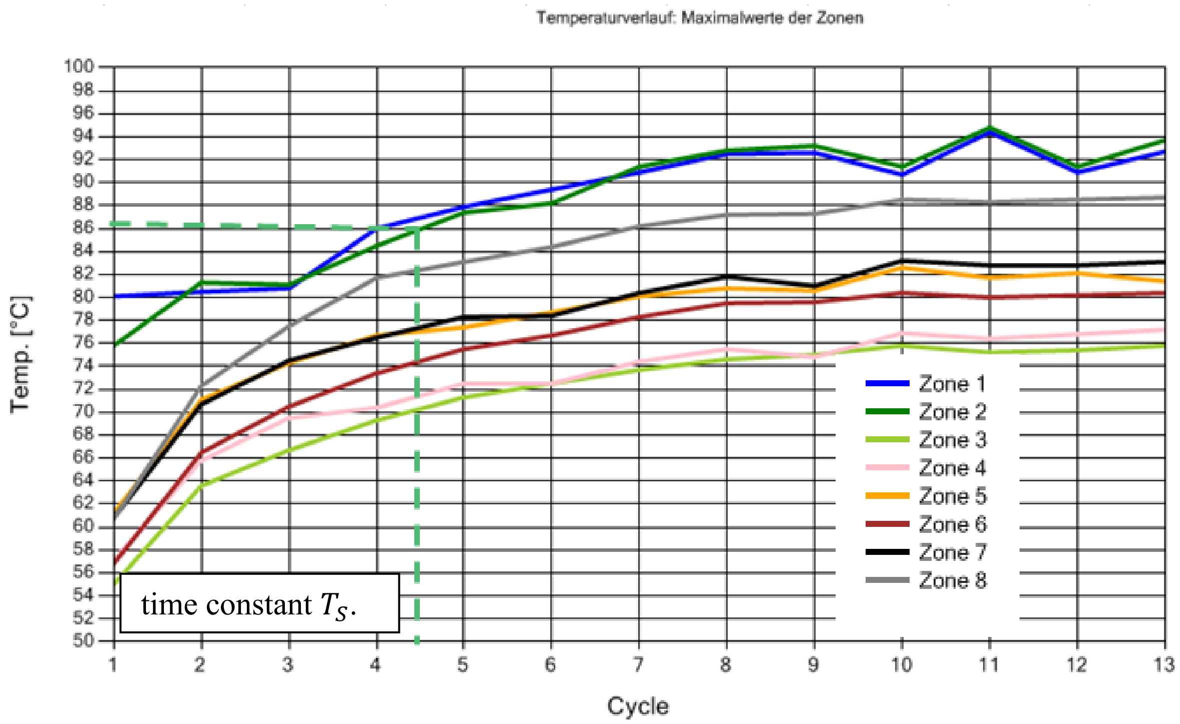

Figure 7: step respone of the opened control loop, coolant flow = 0

For the optimization of the controller parameters, different empiric rules (e.g. from Chien, Hrones and Reswick) were applied. Figure 8 shows some examples for the transient maximum temperatures of the cooling segments with different parameter settings for the gain K_{PR} and the integral time T_N. The derivative time $T_D$was in all cases set to zero. In example a) and c) the empirical optimized parameter settings lead to short rise times with low overshooting. With increasing K_{PR} from 1 in a) to 5 in b), the zones with the smallest T_S (3 and 6) start to oscillate and the loop gets instable. If the T_N is increased, the reduced I-share leads to a prolonged rise time as shown in d).

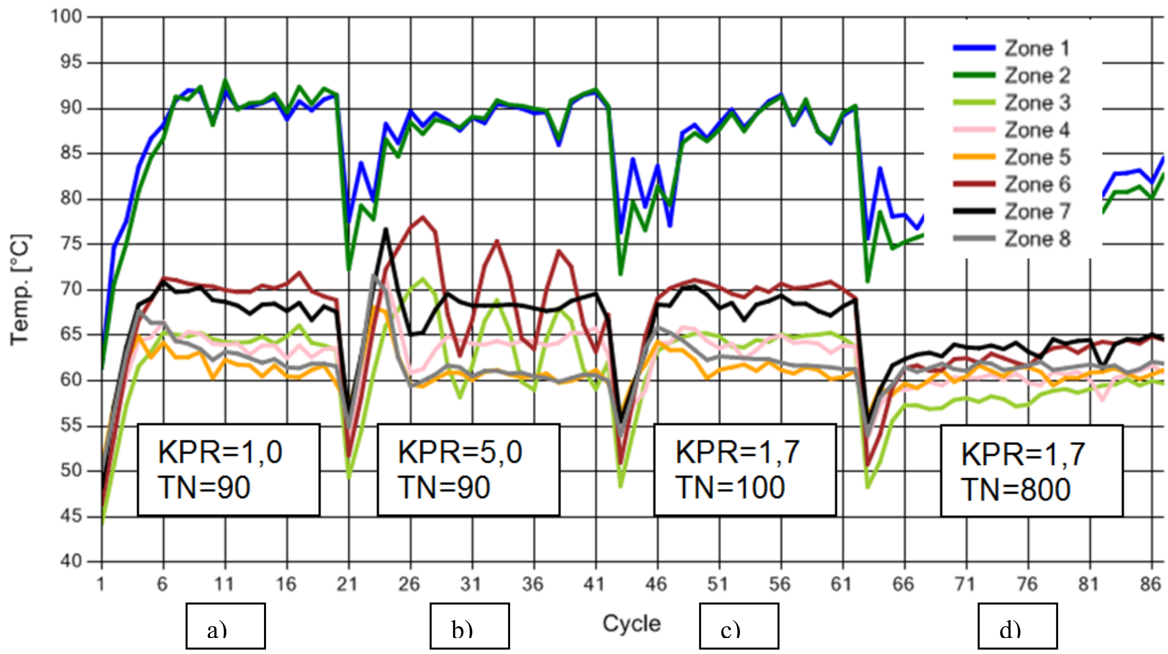

Figure 8: step responses (process start) with closed loop and different parameter settings

The experiments proofed that it is possible to use infrared temperature information from the demolded articles to establish a closed loop control for the mold temperature. Even the most critical operating condition of starting the process can be controlled. In comparison with the established control systems, the inline thermography provides a visualization of the temperatures including hot spots and allows the controlling of the mold temperature distribution. Compared to temperature sensors in the mold, this method is also economically applicable to existing molds due to the availability of cost efficient IR-cameras.

6. QUALITY CONTROL

The IR-temperature information is also usable for the quality control of molded parts, as the following examples show. If the post pressure is reduced stepwise as visualized in Figure 9, the maximum surface temperatures e.g. in zone 2 (Figure 10) start to rise significantly due to the reduction of the contact time between the mold and the shrinking part. A further pressure reduction decreases the temperature close to the gate (due to the significantly reduced amount of material) and increases the temperatures in the surrounding as shown in Figure 11.

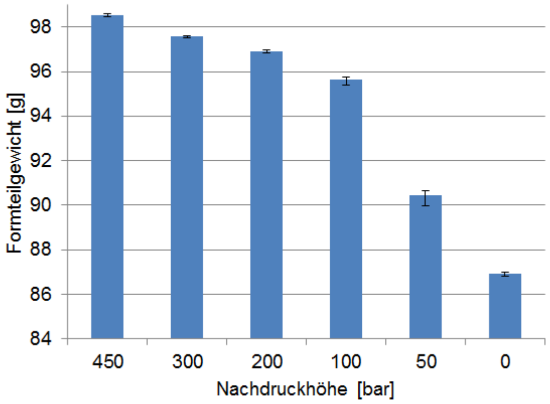

Figure 9: part weight with reduced post pressure

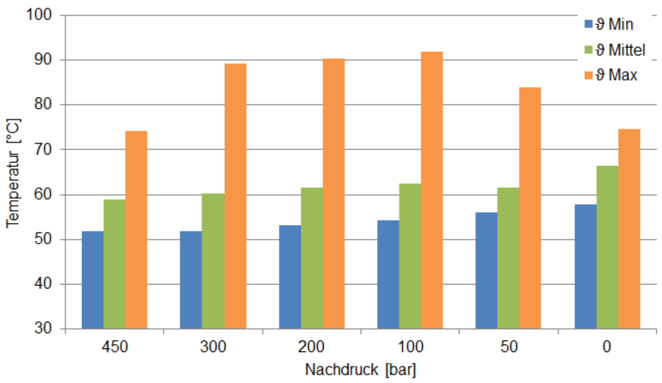

Figure 10: temperatures in zone 2

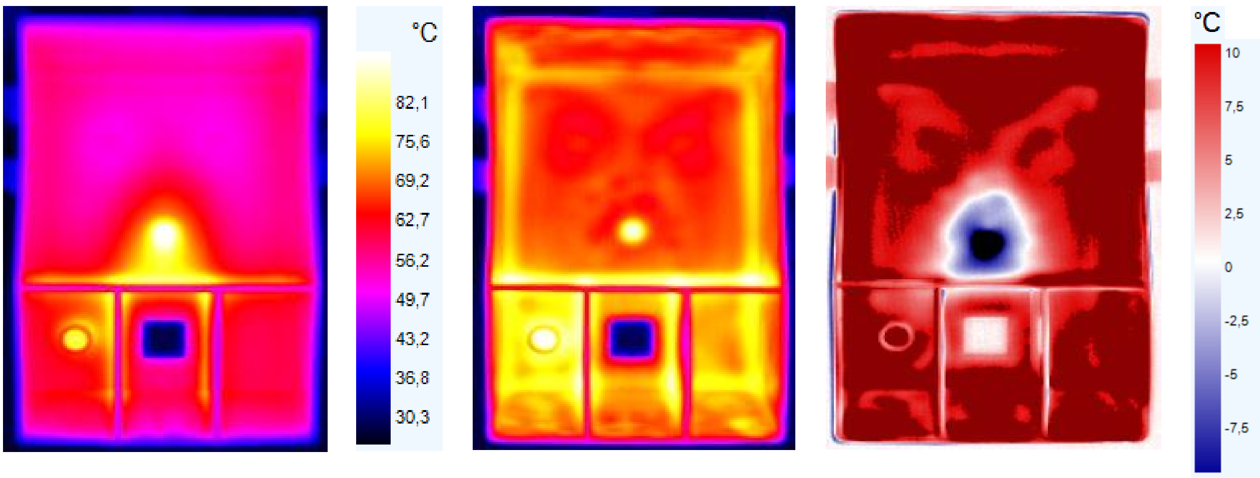

Figure 11: Impact of missing post pressure on temperatures ; left: reference with 450 bar, middle: 0 bar, right: temperature difference between 0 bar and 450 bar

In industrial environments, further experiments were carried out to evaluate the potential of the system with other articles. The following pictures show from left to right the reference, the actual and the difference pictures.

In Figure 12 the short shot in a refrigerator part can be detected due to a temperature difference of 12 °C in the marked area.

Figure 12: part of refrigerator with short shot

Deviations in the coolant temperature may lead to part filling problems of articles with long flow paths and thin walls. The example of a connector part shows the visualization of this situation in Figure 13, where the mold temperature was getting too cold.

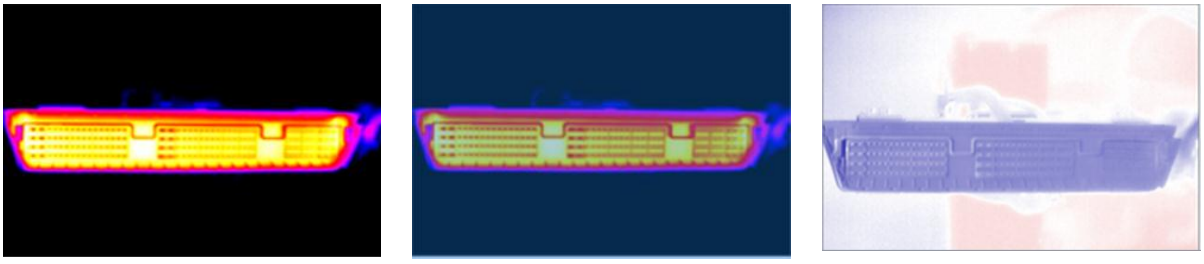

Figure 13: connector housing with too low coolant temperature

Also disturbances in the balance of hotrunner injection systems are detectable as shown in Figure 14, where the black marked gate was partially blocked and the segment was filled through the green marked gate.

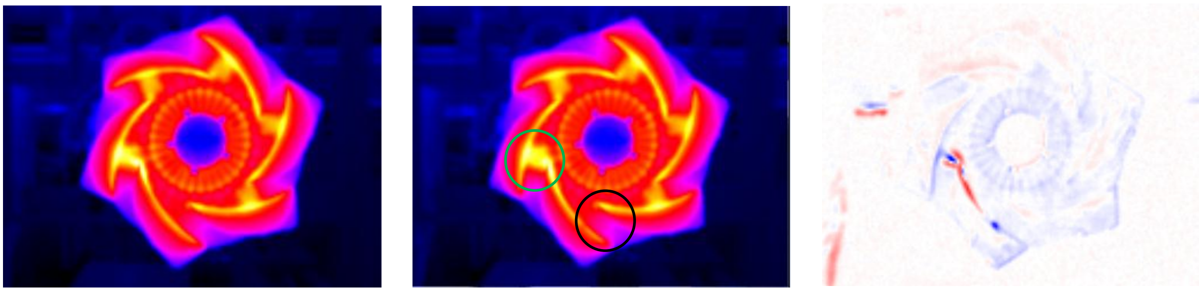

Figure 14: fan wheel with unbalanced injection (1 of 6 hotrunner channels partially blocked)

7. RESULTS

Using inline thermography to control the temperatures of molds in injection molding processes is a reasonable and cost efficient option, providing the possibility to select the areas for temperature measurement after the production of the mold. With optimized PI parameters, even the start of the process can be precisely controlled for segmented cooling systems and start-up scrap can automatically be sorted out.
An additional benefit is the inline visualization of all temperature deviations in comparison to a standard part (e.g. out of the approval process) temperature distribution.
For 100 % quality control, the operation of quality gates based on inline thermography can be an interesting alternative to CCD based systems.

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REFERENCES

[1] F. Johannaber, W. Michaeli, Handbuch Spritzgießen, Carl Hanser Verlag, 2004.

[2] J. Bozelli, J. Lafeber, Use of Infrared Thermal Imaging to Study Mold & Part Cooling. ANTEC. 2004. Proceedings of the 62nd Annual Technical Conference & Exhibition, Vol. L, Chicago, IL, May 16…20. Society of Plastics Engineers,S. 803 ff.

[3] N. Bauer, Fraunhofer-Allianz Vision: Leitfaden zur Wärmefluss-Thermografie, ISBN 3-8167-6754-0, Erlangen, 2005.

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