Analysis of the injection moulding of thick-walled product with Cavity Eye cavity pressure measurement system

András Szűcs PhD[*] college adjunct, *Károly Belina PhD*[*] professor

1. Introduction

The quality requirements for the injection moulding products are increasing, enough to think of the automotive or telecommunication products, which mechanical properties, dimensional accuracy and appearance developed greatly in the last years. Thanks to the appearance of more accurate injection moulding machines, moulds, and more special polymers on the market. One of the corner stone of the continuous production of the right quality product is the correctly set injection moulding technology. Of course, the machine setting means not only the parameters of the injection cycle, but the correct preparation and drying of the raw material, the tempering of the mould and other settings. It makes difficult the reproducibility of production when we work with multi cavity mould due the different filling of the cavities. To test the reproducibility and stability of the technology we can use the monitoring tools of the injection moulding machine. This method is more or less effective, but it has its limits since we do not measure the parameters where the forming happens so confounding factors limit the reliability of the monitoring. The cavity pressure measurement is the only technique that gives a closed feedback for system operation. Switchover based on cavity pressure increases the system stability, product separation based on the pressure curves – by setting correct tolerances - ensures scrap-free production, storing the measured values provides quality control and traceability. Unfortunately, these systems are not widespread in the industrial environment, therefore at the GAMF Faculty of Kecskemét College we developed a new cavity pressure measurement system, which opens new possibilities for the users. In our article we show the potential of the measurement system with the help mould of thick-walled product from a practical point of view.

2. The experiment

For the tests we used the Tipelin R-959A (TVK Nyrt.) type of polypropylene, which is recommended for injection moulding, and has low viscosity, and its flow index is 45g/10 min measured on 230°C and at a load of 2,16 kg.

The experiments were performed on an ARBURG Allrounder 470A injection moulding machine with monitoring system. During the testing/production process the electronic data carrier continuously store the measured values (injection pressure, injection time etc.), so they can be quite easily and quickly analysed later.

For the measurements we used the mould of an altered standard specimen. The inlet system of the mould can be equipped with inserts, so products can be manufactured by side, film, unilateral and bilateral gate. The thickness of the cavity is 4 mm. In both cavity the ejector pins are located at the beginning and at the end of the flow path, through them indirect measurement can be performed. Under the ejector pins we installed our self-developed π-cell pressure sensors. The measuring range of the sensors is 15 kN, which is really necessary since the reaction force is approximately 7850 N in case of a 10 mm diameter ejector pin and 1000 bar cavity pressure. Thanks to the minimized signal-to-noise ratio the measured values are shown in rather big resolution, so even a few N load can be measured accurately, and the characteristic is linear in the entire range. The sensors are not sensitive to temperature change. The signals were processed by "Cavity Eye" measuring system (Figure 1) and software which were developed especially for industrial environment, but suitable for laboratory measurements too. The standard version of the instrument handles 8 channels – sensors – and can be expanded indefinitely. It contains many automated functions, for example electronic access, storage, and compression of all the measuring results, statistical evaluation, automated identification of the mould etc.

.

Figure 1. „Cavity Eye" pressure measuring system

The analysis of injection moulding process

The cavity pressure and hydraulic pressure curves are more or less connected. The injection pressure clearly influences the cavity pressure, but the moulding happens in the mould cavity, so we can only get correct information about the production process if the pressure is examined in the mould cavity. A general cavity pressure and hydraulic pressure curve is shown on Figure 2. The curve can be divided into several distinct sections, which are:

– filling,
– packing,
– holding pressure,
– cooling [1].

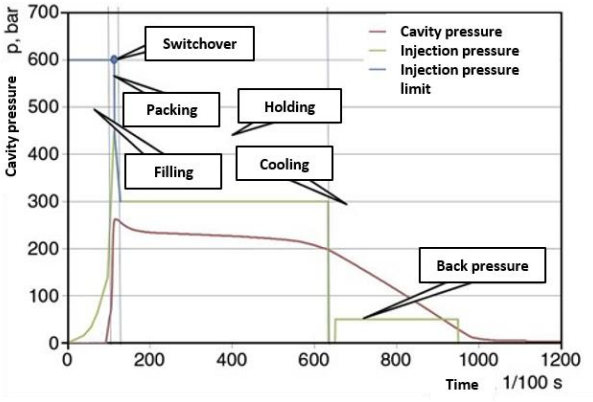

Figure 2. Cavity pressure and injection pressure in function of time

In the filling phase the material flows freely in the cavity. The pressure required to maintain the flow is relatively small, and it primarily depends on the flowability of the material, speed of the melt front and cross-section of the flow. There are fundamental differences between the thin- and thick-walled products. The filling of thin-walled products with long flow path is more complicated, there is less time available, and in the filling bigger pressure formed in the mould cavity while the cooling time also significantly shorter.

In the compression phase the mould cavity is entirely filling up with polymer melt. The material does not flow, so when it is slightly compressed, the cavity pressure is built up in 0,01…0,1 second. Compression basically means that we squeeze several precent more material into the mould cavity than it could contain on atmospheric pressure. (The compressibility of the material can be determined by p-v-T measurement.) After the compression there is a switchover to holding pressure, this means the real built-up injection pressure is reduced momentarily or within a specified "ramp" time to the holding pressure value. The "ramp" can be always set on a modern injection moulding machine, which greatly perpetuates the process, since the PID control electronics is not able to handle steadily momentarily changes. The switchover is one of the most sensitive parameters of the injection moulding process.

During the decrease of the material temperature, the specific volume is decreasing, this is compensated by the injected material in the holding phase. During holding phase decreasing, increasing, and possibly pulsing pressure profiles can be used. Leaving the holding pressure or setting it incorrectly can result in sink marks on the surface of the product or vacuum void inside the product. The holding time is useful until the sealing i.e., when the material temperature in the cross-section of the impediment is decreased under the yield or crystallisation temperature then it solidifies and prevents the flow of material.

In cooling phase, the material continuous to cool, the pressure in the mould cavity decreases, but due the sealing the material does not flow. Therefore, the pressure decrease is approximately proportional to the decrease of the specific volume, i.e. the shrinkage of the product. The negative steepness in the cooling phase is proportional to the cooling speed.

One of the most important machine parameters is the switchover. In industrial environment the most common to set the switchover according to the path, which means that the switchover from speed control to the pressure controlled holding phase happens at a given screw path. In case of modern machines this position can be held with 0,001-0,01 mm accuracy. The fault of system is that it does not take into consideration the external effects on the filling process. In case of the failure or slight wear of the non-return valve, the path of switchover will be constant, although the amount of the injected material will fluctuate in each cycle. The least common method is the switchover according to time. It has the benefit to be able to measure the time with extreme accuracy, therefore it can be used for control. The most effective method in term of stability is to measure the cavity pressure. The pressure sensor is located near the gate or far away from it. If it is located near the gate then the entire filling process is well traceable, if it is at the end of the flow path then the filling of the product can be checked. We get the most information if there are sensors both at the beginning and end of the flow path. This is especially important at thin-walled products. Since the goal is to produce the same product quality in every cycle, the largest stability can be reached by switchover based on cavity pressure, which means a closed feedback [3]. The figure 3 shows the product manufacturing process.

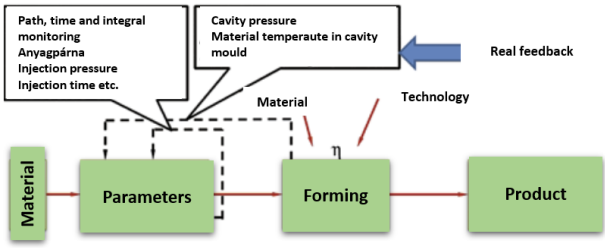

Figure 3. Flow chart of product manufacturing

3. Measurement results

For the experimental production a stable technology was set (table 1.), compared to this the following parameters were changed:

- injection speed ($v_{fröccs}$),
- material temperature (T_a),
- mould temperature (T_{sz}),
- switching point ($s_{át}$),
- holding pressure (p_u),
- holding time (t_u).

Figure 4 shows cavity pressure curves measured in one cycle. 2 sensors per cavity provide the signal, so in altogether 4 curves displayed belong together in pairs. The sensors were calibrated so the experienced differences of the pressure peaks can arise from the differences of the mould geometry. The previously mentioned four phases can be well separated.

By zooming in the rising section of the curve, the filling and compression phase becomes visible (figure 5).

Table 1.
Technological parameters

Material temperature	200°C (240°C)
Mould temperature	30°C (90°C)
Injection speed	80 mm/s (40, 60, 100, 120, 140 mm/s)
Switching point	10 mm (11, 9, 8, 7, 6 mm)
Injection pressure	1500 bar
Holding time	5 s (1, 2, 3, 4 s)
Holding pressure	300 bar (100, 200, 400, 500, 600 bar)

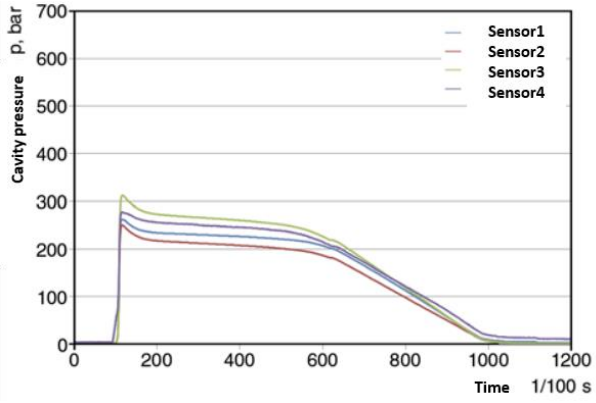

Figure 4. Cavity pressure curve in function of time

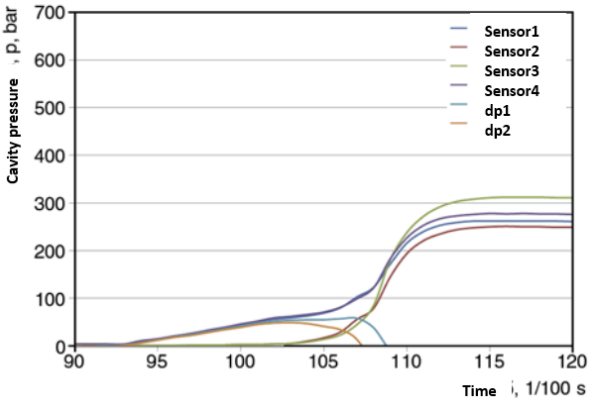

Figure 5. Cavity pressure curve in function of time

The melt reaches the sensors located near the gate in approximately 85ms, although measurable pressure appears only at the end of flow path, after 100ms. The measured pressure difference between the sensors (dp1 and dp2) in the filling phase is almost constant in a short section and proportionate to the material viscosity, the passed time between rising of two signals is proportionate to the injection speed (shear speed).

Table 2 summarises the Δp and injection pressure values.

The curves seen in figure 6 are similar to the flow curve [3]. The explanation for this is that the shear stress is determined by the pressure drop and flow geometry, while the shear speed comes from the flow volume and flow geometry. By increasing the injection speed, the measured pressure difference between the sensors is changing non-linearly, so the material viscosity is decreasing which can be measured on-line with the system. The effect of the material temperature on the flowability is unambiguous. Lower pressure was required to fill the mould cavity with higher temperature plastic. The registered injection pressure shows similar tendency, which has an entirely different explanation. The limit of the injection pressure set on the machine is 1500 bar.

Table 2.
The Δp and injection pressure in function of injection speed

Temperature	200°C		240°C	
$v_{fröccs}$ [mm/s]	$p_{fröccs}$ [bar]	p_1-p_2 [bar]	$p_{fröccs}$ [bar]	p_1-p_2 [bar]
40	380	40	334	34
60	426	45	384	41
80	462	54	391	45
100	495	60	415	48
120	523	61	438	50
140	548	63	458	54

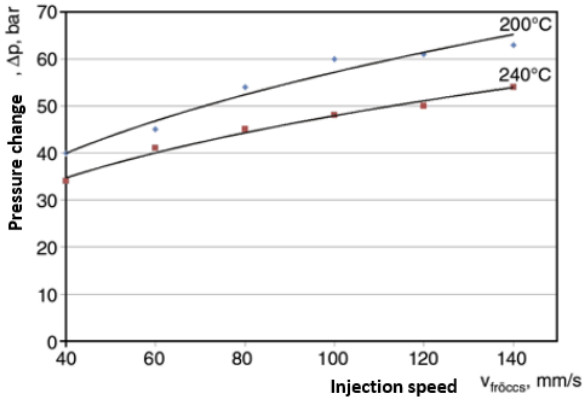

Figure 6. Δp *values in function of injection speed*

The measured pressure in the injection phase is significantly lower than this, which means that this parameter does not play a role in the forming, the real injection pressure can freely build up. The difference can be explained more by the reaction time of the machine, which changes between 0,01 and 0,1s according to the machine type. By increasing the speed of the screw piston, the inertia of the screw is increasing, i.e. it will stop later. The switchover was 10mm at all the settings, but the screw stopped later each time. Figure 7 shows the pressure curve of the 1. sensor in function of injection speed. (To make the comparison of curves easier, in the following we use the measured results of the 1. sensor.)

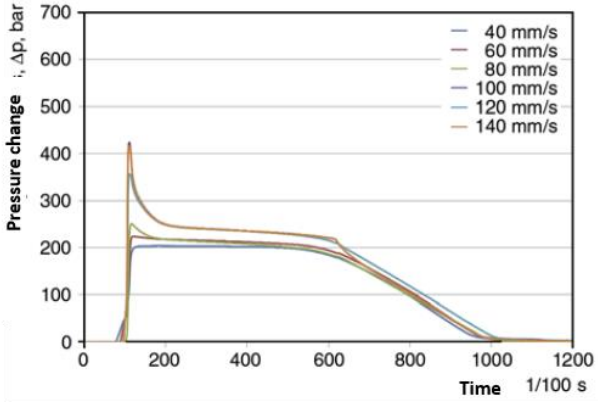

Figure 7. Cavity pressure in function of injection speed

At exact same parameters the injection speed has a significant effect on the cavity pressure. The specimens made at the speed of 120 and 140 mm/s have flash, which can be explained by the high cavity pressure. In case of flash it must considered whether it was formed in the filling or the holding phase. In this case the impulse-like pressure surge slightly opens the mould, and the low viscosity melt forms flash. In cases like this, flash can be stopped unambiguously by decreasing the injection speed, the holding pressure does not affect it.

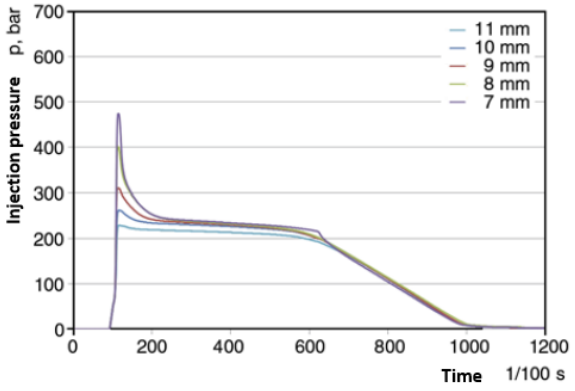

Figure 8. The effect of the switching point on the injection pressure

Changing the switching point brought similar results. At basic setting the switchover from injection pressure to holding pressure happens at the 10 mm position. If the switchover earlier, i.e. at 11 mm happened, it only slightly reduced the holding pressure. This means that the compression happened in the holding phase. If the switchover takes place later, then the injection speed shows the same phenomenon as before. Since the upper limit of the injection pressure was 1500 bar, the injection moulding machine did not limit the real, built up injection pressure. Due the late switchover flash was formed on the part (figure 8.)

To analyse the process faster, worth to examine the filling and compression phase a little more (figure 9.). The pressure curves measured in the filling phase are the same, the lines overlap. The switchover of 11 and 10 mm bends slightly due the relatively early switchover. The curves are running together even in the compression phase, while the injection speed made the curve run-ups steeper or flatter. After switchover we use 300 bar holding pressure at all setting. The decrease of cavity pressure peak over time can be explained by the backflow of the material. There was a 200…250 bar cavity pressure until the sealing. This difference can be explained by the compressibility of the polymer, the not-Newtonian flow, and the structural changes in the flow cross-section during the cooling [4].

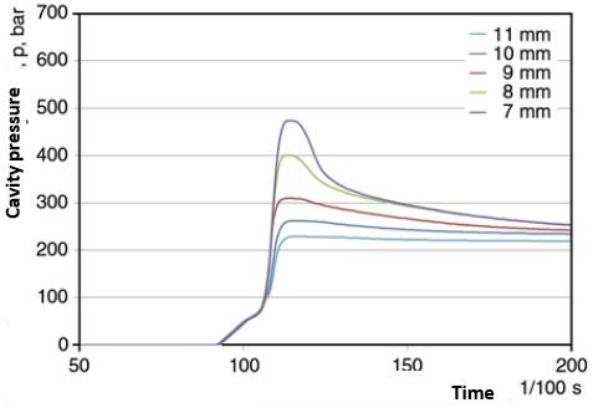

Figure 9. Effect of the switchover on cavity pressure

The holding time is usually determined by the mass measurement of the part. With cavity pressure measurement system, the effective holding time can be determined faster and more accurately (figure 10). Since all the parameters are constant, the curves run together until the end of the holding time. When the holding is shorter than sealing it can result in a sudden break, which also the result of the free material flow. If the holding time is longer than the sealing time, it is not shown in the curve, because the material parts frozen in the impediment do not allow either inflow or outflow. After sealing – in the cooling phase – the steepness of the curves is approximately constant, which is analysed in the cooling test.

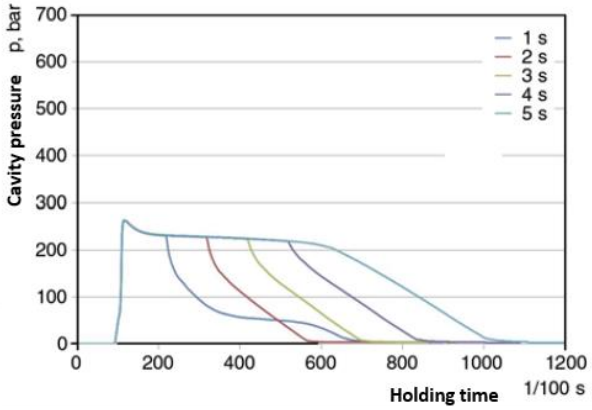

Figure 10. The effect holding time on cavity pressure

The testing of holding pressure brought very interesting results (figure 11). The cavity pressure is slightly lower than the set value. The reason for this was explained previously. When the holding pressure is lower than the cavity pressure, then backflow formed in the impediment and the pressure decreases. But when it is higher, then the compression is formed by holding pressure, reaching the pressure peak becomes slower, and it stays on the same value until the sealing.

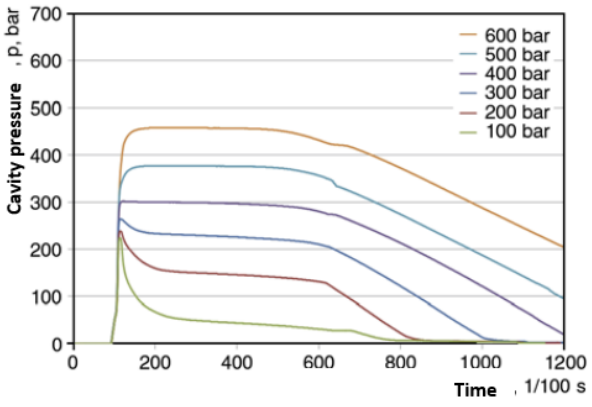

Figure 11. Effect of the holding pressure on cavity pressure

At either of the settings are the specimen with flash, although the cavity pressure was significantly higher than during the change of injection speed. The reason of this is that the shell of the part is continuously cooling during the filling. When the temperature of shell layer decrease under the crystallisation temperature, then a solid shell surrounds the melt. Accordingly, the melted material is not able to break through the shell, flow into the dividing plane, form flash. Consequently at the production of thick-walled products the holding pressure value should be profiled in order to reduce the sink marks, recommended to increase it under time.

Figure 12 shows the effect of material temperature on cavity pressure. It is immediately apparent that by increasing the temperature of the plastic, the cavity pressure is increasing, and the sealing also happens more and more later. Above 230°C the 5 seconds long holding counts as short, the reason for this the higher temperature melt seal later.

The function in figure 13 are first derivative in time of the figure 12 curves. It contains many interesting points in terms of process analysis.

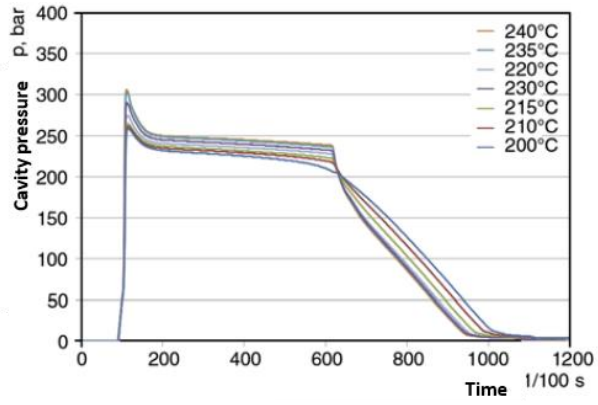

Figure 12. Effect of material temperature on cavity pressure

It shows well the influence of the material temperature on moulding process. In the compression phase can be seen the first and the biggest peak in a positive direction, which a negative peak follows, this is proportionate to the outflow rate of the material. In the holding phase a negative steepness can be experienced, the pressure slightly decreases. The next negative peak results in a more significant change in function of temperature. Continuous transition is shown between the switchover and cooling, when the sealing happens, if the holding time is short, then there is a negative peak again. In cooling phase all the steepness is constant, since after the sealing the cooling speed does not change substantially.

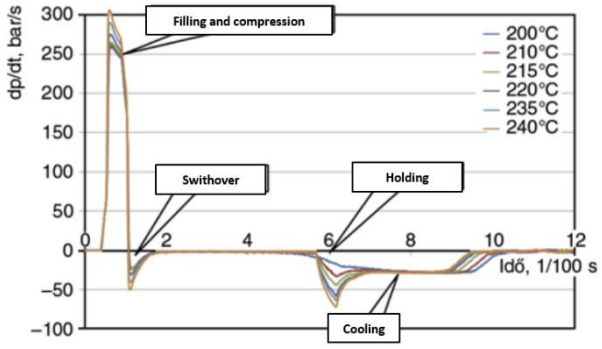

Figure 13. First derivative in time of the cavity pressure curves at different material temperatures

The mould temperature influenced the curves similarly to the material temperature but did not increase the pressure peak in the same amount (figure 14). By increasing the mould temperature, the sealing time shifts to later again. At 53°C the 5s holding time is not enough, the material flows out of the cavity even before the sealing happens. In the holding phase the pressure decreases less at a higher mould temperature. This can be explained by the slower cooling and the slower decrease of specific volume.

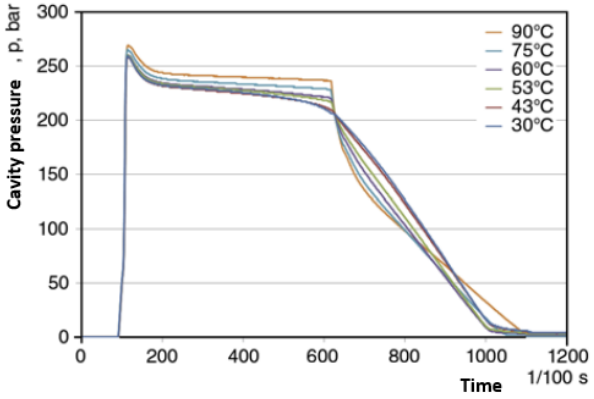

Figure 14. The effect of mould temperature on cacity pressure

By evaluating the derivative of figure 14, the effective holding time and cooling speed can be verified (figure 15). The higher mould temperature results in slower cooling, which is shown well on the diagram. The analysis of the derived function is used in the algorithm of the Cavity Eye control and interfering process, which is under development.

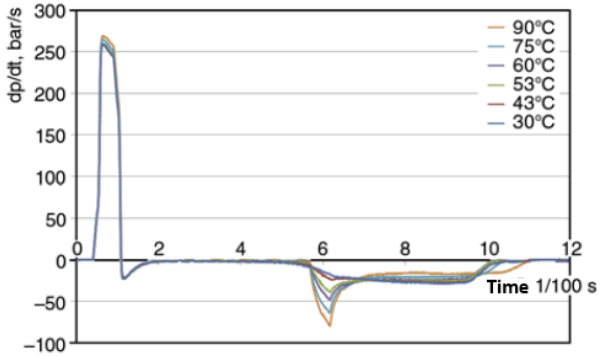

Figure 15. First derivative in time of the cavity pressure curves at different mould temperatures

4. Summary

As result of the last years research, we developed a cavity pressure measuring system, which includes the development of the measuring cells, hardware components, and software. The instrument was created according to the industrial requirements, but it is suitable for laboratory measurements too. In our article we introduced the possibilities of the pressure measurement and the conditions of the injection moulding process. The measurement results demonstrate well how each technological parameter effects the four phases of injection moulding. The analysis and control of the injection moulding process with the curves and the first

time derivate of the curves ensures further automatization possibilities. The use of the system can make production launch easier and faster. In case of the manufacture of faulty products it helps to determine the cause of the problem, and to sort and separate the scrap due the instability of the technology.

Bibliography

[1] Ming-Shyan Huang: Cavity pressure based grey prediction of the filling-to-packing switchover point for injection molding, Journal of Materials Processing Technology, 183, 419–424 (2007).

[2] Ho Yin Wong, Ka Tsai Fung, Furong Gao: Development of a transducer for in-line and through cycle monitoring of key process and quality variables in injection molding, Sensors and Actuators, A 141, 712–722 (2008).

[3] Sz"cs, A.: Rheological and thermal analysis of the filling stage of injection moulding, eXPRESS Polymer Letters, 6/8, 672–679 (2012).

[4] Pantani, R.; Coccorullo, I.; Speranza, V.; Titomanlio, G.: Morphology evolution during injection molding: Effect of packing pressure, Polymer, 48, 2778–2790, (2007)