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Influence of the process control type on thermoplastic injection moulded part quality

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Abstract

This paper analyses the incidence of the process control type on the production stability of thermoplastic injection moulded items. Quality criteria are part weight, dimensions and mechanical properties (impact toughness). Three process control modes were assessed. The first one is a regular control of the hydraulic pressure (HPC), the second, an advanced closed loop control of the polymer melt pressure during the holding stage (PPFC), and the last, a cycle-to-cycle self-adaptive control (APPFC). In the last case, the filling stage is used to record the experimental data required to feed a simplified analytical model, which calculates the holding pressure to be applied to the polymer according to the actual thermal and rheological state of the injection process.

A significant benefit on parts weight stability of the PPFC and APPFC process controls, compared to the HPC one, was proved whatever the configuration is (different materials, moulds and machines). The ability of these systems to reduce the scattering of volume moulding shrinkage was also highlighted in one specific case (PBT). Moreover, it was observed that the total volume shrinkage is of lower absolute value for PPFC and APPFC modes than for the classical one. This experimental result was explained theoretically by transposition of injection moulding cycles on a PVT diagram. Regarding impact strength, the slight negative effect due to additional internal stresses induced by the polymer pressure based controls with (APPFC) or without model (PPFC) remains of secondary importance compared to the benefits obtained on dimensional precision and stability. On the other hand, these modes generate a decrease in the scattering of the impact strength.

1 Introduction

In order to face the more and more demanding specifications of the current thermoplastic processing industry, companies have to find new solutions to maintain their position in this very competitive market. Two important issues for the injection moulding sector are the quality and the reproducibility of injected parts, and the reduction in scrap. They are directly connected to the complex interactions between the different variables involved in the process (material properties, temperatures...). Natural changes, even of small amplitude, of these parameters can generate unacceptable drifts of the part final properties. Therefore, these fluctuations have to be taken into account to expect further improvement of the injection process. Since the regular control modes are often at their limits, new systems have to be developed. Several approaches have been explored, such as the use of thermo-mechanical models, expert systems or artificial neural networks [e.g. 1-8]. Most of them have the drawback of being currently intricate to implement or require extensive calculation time, incompatible with an on-line monitoring and control of the process. To overcome this problem, one solution consists in using simplified physical models that are based on a limited number of key variables [e.g. 9-13]. This approach was chosen for the present study since it requires a short calculation time, which is adequate to adjust the parameters for each injection cycle, and to get eventually a significant and cost-effective improvement of the process. The assessment of this new patented system for different configurations is presented in this paper (US patent no. 6 019 917 A, French patent no. 2 750 918, European, Canadian and Japanese patents pending).

2 Comparison between standard and advanced process control modes

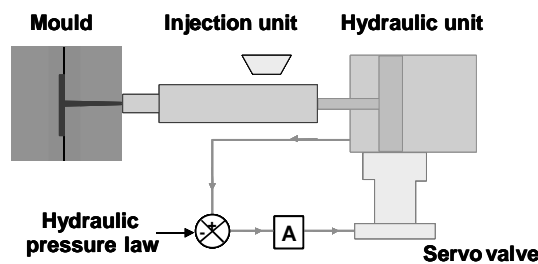
2.1 Principles of the process control modes

The goal of the present study was to develop a system providing a better control of the weight and the dimensions of injected items. Therefore the main focus was put on the holding stage of

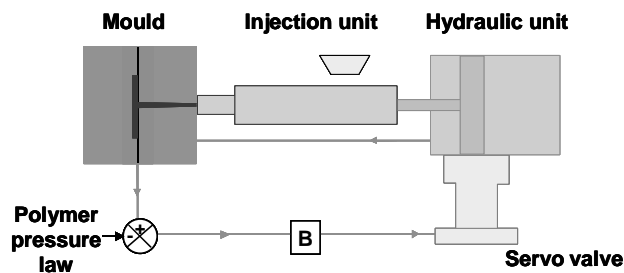
the injection process, considering that this stage is determinant for the stability of these properties [14]. The injection phase (filling stage) is considered as secondary but is however crucial to evaluate the actual state of the system as described below. The quality parameter used to assess and control the system is the weight of the parts, only parameter of easy access in the production line. Assuming that weight and dimensions are related, the control of the weight should also have an influence on the dimensions, as it will be assessed in the next section.

Up to now, most injection moulding machines control the pressure during the holding stage only through the hydraulic group, without any connection with the actual polymer pressure within the mould (HPC mode : Hydraulic Pressure Control, Fig. 1.a). This means that the latter pressure can change along the production sequence and even from one cycle to the other because of the evolution of the pressure transfer law between the hydraulic group and the polymer in the cavity. This evolution is related to many factors such as the tool and hydraulic oil temperatures or the material visco-elastic properties, and is therefore difficult to assess. The result is a large scatter of the final properties (weight, dimensions...) and a high scrap ratio. This problem is particularly severe when large fluctuations of the parameters appear (e.g. start of production, change of material grade or batch, addition of recycled material...), but can also

a. Hydraulic Pressure Control (HPC)



b. Polymer Pressure Feedback Control (PPFC)



c. Adaptive Polymer Pressure Feedback Control (APPFC)

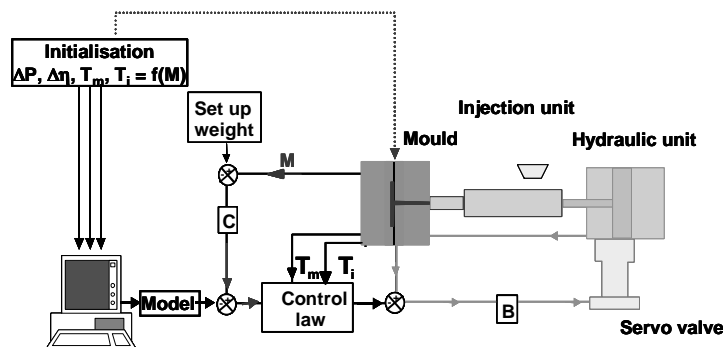


Figure 1 : Function chart for the different control modes

be determinant in stabilized productions (small local change of temperature or material properties...) when tight tolerances are specified.

One solution to overcome this problem is to measure directly the pressure of the polymer melt within the cavity and use it as a feedback for a closed-loop control of the hydraulic group (PPFC mode : Polymer Pressure Feedback Control, Fig. 1.b). This way, the applied pressure is similar from one part to the other, resulting in a lower scatter of the properties. The drawback of this system is that the polymer pressure is constant whatever the temperature and the material properties are. However, these parameters have an influence on the final properties and should therefore be taken into account to get a further enhancement of the reproducibility.

This aspect was introduced in the previous control system by adding an adaptive module to adjust the injection pressure according to the actual thermal and rheological environment of the process (APPFC mode : Adaptive Polymer Pressure Feedback Control, Fig. 1.c). The system is based on a simplified analytical model that considers that the weight (M) of the parts is correlated to the main parameters of the process such as the injection (T_i) and mould (T_m) temperatures, the holding pressure (P) and the polymer viscosity (η). All parameters of secondary significance for the weight stability are neglected in order to have a manageable model. Equation 1 gives the general form of the model. By reversing this equation, the holding pressure, only easily adjustable parameter, can be connected to the other parameters to get the command law (Eq. 2).

$$M = f(\eta, P, T_m, T_i) \quad (\text{Eq. 1})$$

$$P = g_1(\eta, M, T_m, T_i) + g_2(M_0 - M) \quad (\text{Eq. 2})$$

Based on equation 2, it becomes easy to determine the holding pressure required to maintain the weight at the target value, whatever the magnitude of the perturbations acting on the system is. The corrective function g_2 takes into account the possible gap between the targeted weight (M_0) and the actual weight of the last part (M), avoiding any long-term drift. This function is adjusted for every cycle so that the control law is refined during the production. The use of filters eliminates adjustments of weak amplitude in order to avoid disturbing a steady production.

To run the system, it is therefore necessary to know the weight of the last part, the mould temperature and the viscosity of the polymer (the effect of the injection temperature T_i is included in the viscosity η). These parameters are measured in real time and for each injection cycle thanks to the instrumented tooling (pressure and temperature sensors). Considering the limited time available for the measurements and the targeted application, the measurement of the standard viscosity is neither possible nor essential. Therefore, only a viscosity index is determined through integration of the polymer pressure signal in the injection nozzle over a given period of time. Then, the system calculates automatically the holding pressure that has to be applied during the injection cycle in progress in order to take into account the actual condition of the system and the possible perturbations.

The model developed in this study is based on the assumption that, in an industrial process, the parameters oscillate in a limited range. The general non-linear behaviour can therefore be locally linearized (Eq. 3). The parameters of the law are calculated through a calibration protocol based on designed experiments. A multiple linear correlation analysis using the least square method gives the parameters of the command law (Eq. 4) after solving the system of four equations and four unknown factors resulting from the minimization of the error [15]. The parameters a_i and b_i are specific to each polymer/tooling/machine set.

$$M = a_0 \cdot T_m + a_1 \cdot \eta + a_2 \cdot P \quad (\text{Eq. 3})$$

$$P = b_0 + b_1 \cdot T_m + b_2 \cdot \eta + b_3 \cdot M \quad (\text{Eq. 4})$$

2.2 Assessment of the advanced control modes for various configurations

The assessment of the polymer pressure based systems was realized for a wide range of typical materials and equipment configurations using the part weight as quality criterion (experimental details available elsewhere [15]). For laboratory scale productions, perturbations were generated deliberately in order to test the system. A thermal perturbation was therefore introduced in the system by restarting the production after a one-hour break. The material properties were modified at the 50th part by changing the grade or the supplier of the material, or by adding recycled material. The coefficient of variation CV (standard deviation / average ratio) was used to compare the performance of the different process control modes.

Figure 2 shows the evolution of the weight during the production of 100 parts made of 40 %-wt short glass fibres reinforced polyphenylene sulfide (PPS) with a configuration corresponding to the fourth line of table 1. One can see that with the PPFC mode, both thermal and rheological perturbations are still significant but their effect on the weight stability is reduced (- 22 %). In the case of the APPFC mode, the perturbations almost completely disappear and the weight is very reproducible. The scatter is 86 % smaller than with the classical HPC mode. The results for all the configurations assessed in the study are summarized on table 1. Globally, the APPFC mode reduces the scatter at least by a factor 2 compared to the regular mode, and has an efficiency up to 7 times higher than the polymer pressure control mode without adaptive model. The efficiency of this system is therefore clearly validated.

Table 1 : Decrease in weight scatter for different material/mould/machine configurations and process control modes

Material	Part	Production size	Mould		Runners	Injection moulding machine	Gain in weight stability compared to HPC [%]	
							PPFC	APPFC
PP	Set of test specimens (ISO1 + Vicat)	100 sets	Single cavity		Cold	Hydraulic 900 kN	48	85
PBT							19	43
PP + 30 %-wt short glass fibres							12	74
PPS + 40 %-wt short glass fibres							22	86
PP	Semi-industrial (box and lid)	60 sets	4 cavities	balanced	Hot	Hydraulic 3500 kN	49	81
				unbalanced	Cold		64	79
							57	68
PBT	Set of test specimens (ISO1 + Vicat)	100 sets	Single cavity		Cold	Electric 800 kN	47	78
PP	Industrial (bucket)	2500 parts (8 hour shift)	Single cavity		Hot	Hydraulic 3300 kN	22	48

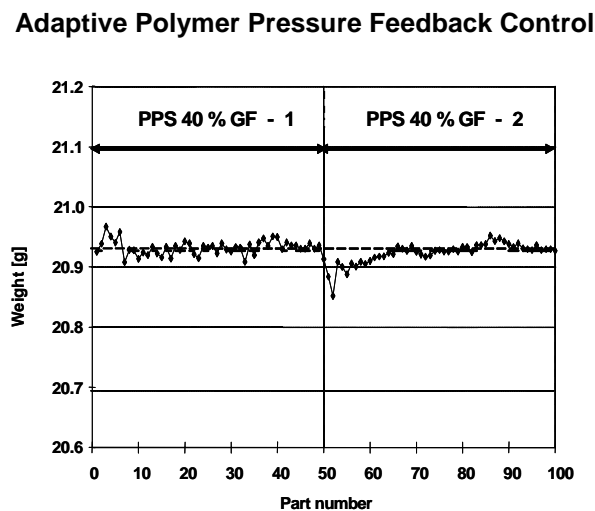
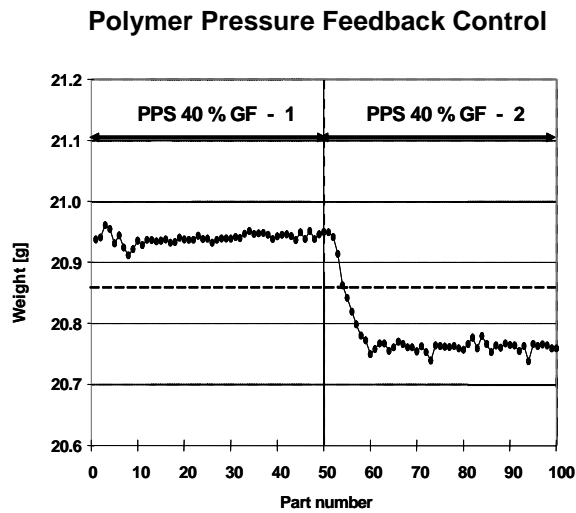
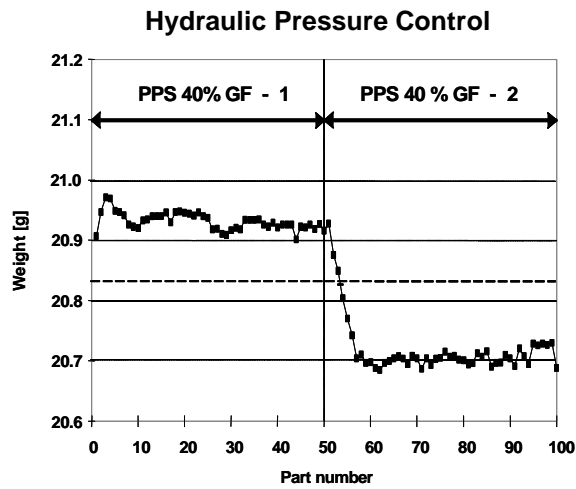


Figure 2 : Evolution of the specimens weight during the processing of 40 %-wt short glass fibres reinforced PPS with the different control modes (grade 1 : Ticona® Fortron 1140L6, MFI = 20 g/10 min, colour : black; grade 2 : Ticona® Fortron 1140L4, MFI = 10 g/10 min, colour : brown; dashed line : average weight)

By controlling the weight of the injected parts, the system developed in this study was also expected to control the dimensions, considering that there should be a relationship between size and weight. The influence of the process control mode on the dimensional stability was therefore investigated through the measurement of the linear and volume shrinkage defined as follow :

$$\text{Linear shrinkage} \quad S = (D_M - D_P) / D_M \quad (\text{Eq. 5})$$

$$\text{Volume shrinkage} \quad S_V = (V_M - V_P) / V_M = 1 - [(1-S_1) \cdot (1-S_2) \cdot (1-S_3)] \quad (\text{Eq. 6})$$

with D the considered dimension, V the volume and S_i the linear shrinkage following one direction (thickness, length, width). The subscripts M and P denote the mould and the part respectively.

This analysis was performed in one specific configuration corresponding to the second line of table 1. The polymer was a PBT (Pocan[®] B 1305) from Bayer[®]. A blend containing 20 %-wt of recycled material was used from the 50th part to generate a rheological perturbation. The dimensions were measured with a three-dimensional measuring machine with a precision of $\pm 5 \mu\text{m}$.

Figure 3 shows the evolution of the weight and the shrinkage (2 days after injection) along the production shift. Table 2 compares quantitatively the effect of the different control modes. Globally, one can see that the use of the advanced systems in the case of PBT induces a noteworthy reduction in the weight scatter. The analysis of the shrinkage scatter from one control mode to the other shows that the trend is the same for both the weight and the volume shrinkage. Therefore, as expected, the advanced control modes based on the control of the weight also have a positive influence on the dimensional stability. However, the volume shrinkage represents an average value of the shrinkage following the different directions. If we look at these properties separately, the result can be of varying quality depending on the direction considered, especially for the width of the specimens. Nonetheless, the dimensional stability is globally enhanced. Similar measurement carried out on the functional dimensions of industrially moulded parts over an 8-hour shift (conditions corresponding to the last line of table 1) confirmed the benefit brought about by the advanced PPFC and APPFC modes. Respectively 15 and 30-% decrease in the scatter of PP bucket diameter was recorded.

The comparison of the absolute values of the shrinkage for the 3 control modes (table 2) shows that the systems based on the polymer pressure feedback generates slightly lower total volume shrinkages (measured after annealing). This can be explained on the basis of PVT charts.

Table 2 : Influence of the process control mode on the weight and volume shrinkage stability of PBT parts

	HPC		PPFC			APPFC		
	Average	CV	Average	CV	Gain PPFC/HPC	Average	CV	Gain APPFC/HPC
Weight	16.431 g	0.047 %	16.472 g	0.038 %	19 %	16.470 g	0.027 %	43 %
Shrinkage 2 days after injection	6.7 %	12.4 %	7.8 %	7.7 %	38 %	7.3 %	6.7 %	46 %
Shrinkage 7 days after annealing*	8.4 %	8.5 %	7.6 %	6.6 %	22 %	7.7 %	7.1 %	16 %

*120°C, 4 hours

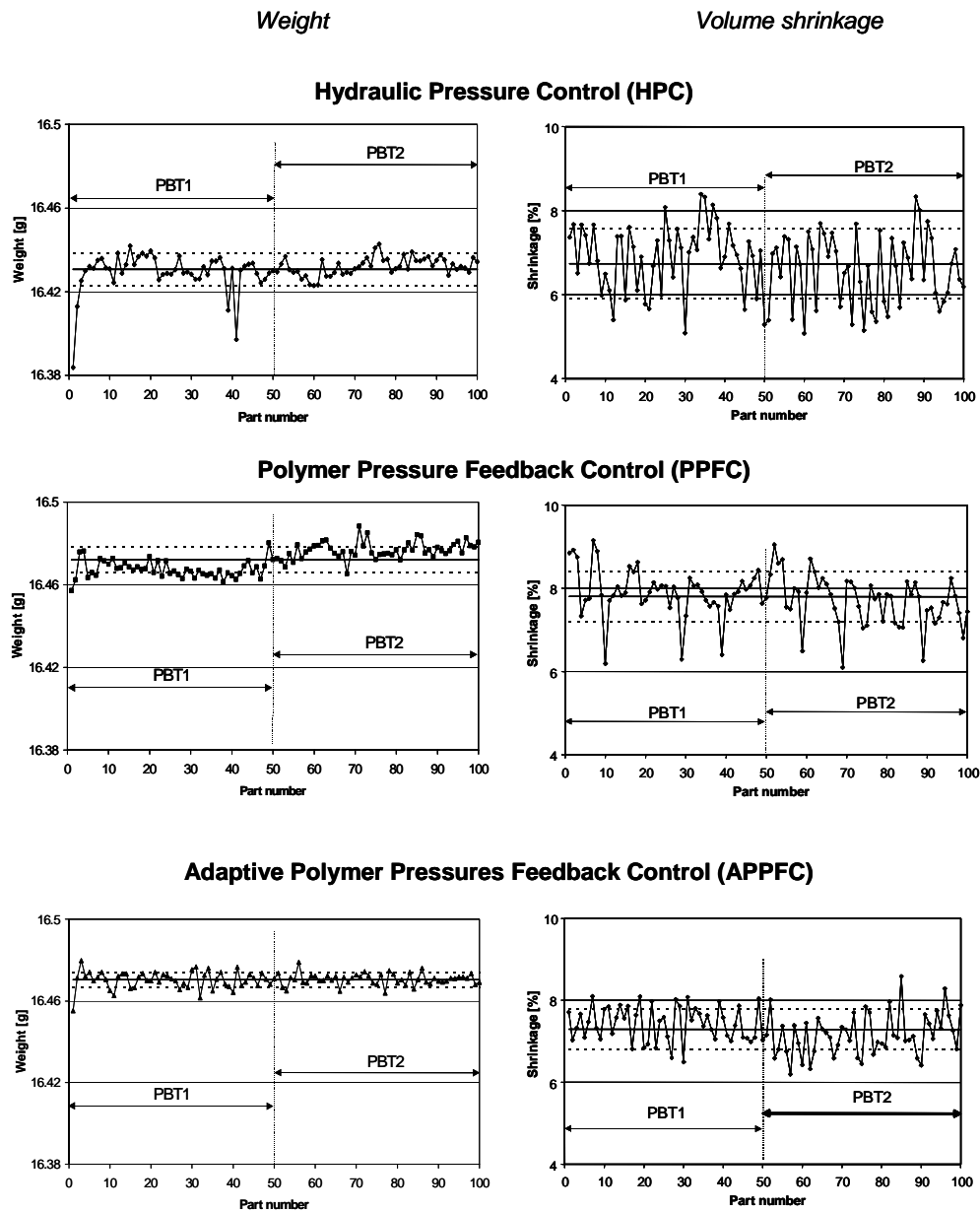


Figure 3 : Evolution of the weight and volume shrinkage during the processing of PBT specimens with the different control modes (PBT1 : Pocan[®] B 1305, MFI = 57 g/10 min; PBT2 : Pocan[®] B 1305 + 20 %-wt recycled material, MFI = 60 g/10 min; solid line : average weight, dashed lines : average \pm 1 standard deviation)

Figure 4 shows the thermodynamic routes followed by the polymer for the different systems. They are obtained from the polymer pressure measurements and the calculation of the temperature profile within the specimen and its time dependence. This latter data is obtained by solving the heat equation (Eq. 7) using the finite difference method. The initial temperature of the walls is given by equation 8. The additional heat due to the exothermal crystallisation and the influence of the pressure on the thermal and physical properties are neglected. Using the temperature profile, it is then possible to calculate the average temperature "through the thickness" as a function of time using equation 9.

$$\rho \cdot C_p \cdot \frac{dT}{dt} = k \cdot \frac{\partial^2 T}{\partial y^2} \quad (\text{Eq. 7})$$

$$T_w = \frac{b_m T_m + b_0 T_0}{b_m + b_0} \quad \text{with} \quad b = \sqrt{k \cdot \rho \cdot C_p} \quad (\text{Eq. 8})$$

$$T_{av} = \frac{1}{h} \cdot \int_0^h T(y) \cdot dy \quad (\text{Eq. 9})$$

with T the temperature
 $T_{0, m, w}$ the injection, mould and wall temperatures
 T_{av} the average temperature through the thickness
y the location through the thickness
h the thickness of the part
t the time
 ρ the density
 C_p the specific heat
k the thermal conductivity

Based on figure 4, an estimate of the total volume shrinkage after annealing (equilibrium state) can be obtained from the difference between the specific volume when the 1-bar isobar is reached, and the specific volume at room temperature (ΔV in fig. 4; division by the specific volume at room temperature to get the total shrinkage). The results (table 3) show that this simple calculation is qualitatively in accordance with the experimental observations. The estimated shrinkages are of the right order of magnitude and the hierarchy between the different modes is respected.

Considering the change in the thermodynamic route followed by the polymer during its

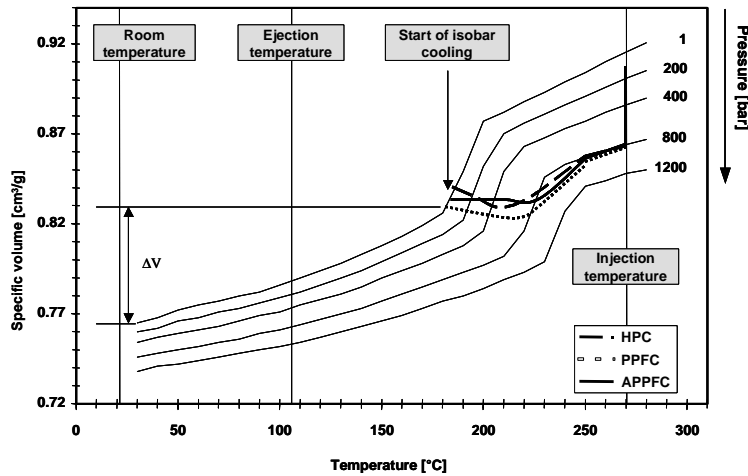


Figure 4 : PVT chart of PBT and thermodynamic routes for the different process control modes

Table 3 : Total volume shrinkage of PBT

Process control	Experimental [%]	Calculation [%]
HPC	8.4	9.6
PPFC	7.6	8.5
APPFC	7.7	9

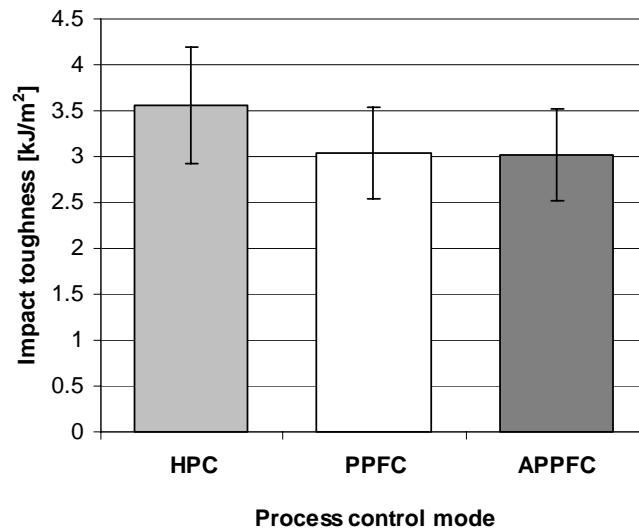


Figure 5 : Influence of the process control mode on the impact toughness of PBT

processing and especially the additional pressure it has to undergo, it is of interest to check if the improvement of weight and dimension stability was damaging to the mechanical properties. In order to get a quick assessment of this issue, Charpy impact toughness tests were carried out to highlight the possible increase in the internal stresses. The tests were realized on notched specimens with an impact energy of 7.5 J. The results presented in figure 5 show that the advanced PPFC and APPFC systems come along with about 15-% decrease in the impact toughness. This can be related to the reduction of energy dissipative defect (micro-voids) due to the densification of the material and additional internal stresses due to the higher average pressure. In compensation, the impact toughness scatter is slightly reduced (-7 %). The advanced process modes have therefore a slight negative effect on the impact properties. However, the global result is totally positive considering the improvement of the reproducibility of the weight, the shrinkage and the impact properties.

3 Conclusion

The assessment of the injection moulding process control modes presented in this study clearly shows the interest of the polymer pressure based systems to get a better control and a better reproducibility of the final properties of injected items. The addition of the adaptive module is a step forward in the control of the process, and has a large potential in highly demanding productions. The detailed analysis of the injection moulding of PBT specimens showed that there is a tight relationship between the control mode, the weight, the dimensions and the mechanical properties. The present advanced system proved to control the weight and the volume shrinkage of the parts efficiently, whereas some increase in the scatter of one dimension, and a small loss of impact toughness was observed. The global results remain however very positive.

4 Acknowledgements

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