Strojniški vestnik - Journal of Mechanical Engineering 54(2008)4, 258-265
UDC 678-1
Paper received: 6.12.2007
Paper accepted: 15.5.2008

Large Thermoplastic Parts Quality Improvements Using Monitorized Nozzle

Angel Fernandez* - Daniel Mercado - Carlos Javierre - Manuel Muniesa
University of Zaragoza, Faculty of Mechanical Engineering, Spain

Rheological behaviour control of thermoplastic material is critical to achieve reliable production series free of defects such us flashes or short shots. Defects are especially critical when injecting large parts if stability of processing parameters cannot be achieved. Viscosity variation during production depends specially of lot of raw material and programmed parameters concerning temperature. Understanding rheological behaviour of molten material in injection nozzle is critical to obtain repetitive series of large parts free of defects. In this paper apparent viscosity was obtained using monitorized nozzle and used as an input to MoldFlow analysis to predict defects. The Simulation model included a two different cavities mould for washing machine tubs made of talc filled polypropylene, hot runner manifold and the machine nozzle. To validate analysis several complete series of parts were injected using a nozzle with two pressure and temperature sensors in a heated thick cylindrical channel, and a screw displacement sensor. Previously the nozzle was validated testing the effect of pressure losses with shear rate variation; apparent viscosity with pressure variations; and others such as viscous heating of polymer. Part defects were characterized using statistical analysis of registered parameters during filling and packing phase of the mould. Simulations of identical experimental parameters for correct and failed parts were used to validate results and characterized the defects.

Keywords: nozzles, polyolefins, viscosity, injection moulding, pressure measurement, temperature measurement

0 INTRODUCTION

This paper summarizes the research work developed by the Mechanical Engineering Area of the University of Zaragoza in cooperation with Foundation AITIIP technological center.

The results are focussed to determine apparent viscosity values of talc filled polyolefins in the nozzle of the injection moulding machine and to register operational parameters during injection of large parts such us bumpers and washing machine tubs in order to establish relationships with typical defects like flashes or short shots.

There are different methods for viscosity measurement of molten polymers [8] to [10]. The capillary rheometer determines the relathionships between viscosity and shear rate, temperature and pressure variations. For this reason this is the most used way to fully characterizate the rheological behaviour of a thermoplastic grade in order to develope further calculations such us injection moulding simulations.

One of the goals of this research work is to determine apparent viscosity in an injection moulding machine during operation [10]. Some advantages can be gained with this technology. First is a real-time viscosity calculation of the raw material used for producing injected parts which is highly dependent of the lot of supplied material. Second is the monitorization of the variations in viscosity values on-line to advance potential fails in injected parts. Third is the influence of scale effects that differ from measurements made through a capillar channel less than 1mm diameter and those made through mould and machine channels from 2 to 20 mm thickness. Other is the information obtained about the injection moulding processing parameters on-line, the possiblity to establish relationships with part defects and the additional option to determine the properties of materials that cannot be tested in the laboratory such us recycled materials and re-used scrap material.

The injection moulding of large parts through very large series over than 1,000 cycles per day is critical because very small defects like

*Corr. Author's Address: University of Zaragoza, Faculty of Mechanical Engineering, C.P.S Torres Quevedo, María de Luna, 3, 50018 Zaragoza, Spain, afernan@unizar.es

short shots and flashes are highly dependent on the viscosity of the material and it can vary depending the lot of raw material. This complex process can be improved using especial sensors for pressure and temperature measurement in the nozzle of the machine. They will be usefull for apparent viscosity determination and also for small variations detection in processing parameters that could induce these defects that affect to less than 1% of the part but force to reject heavy parts and even stop the production lines.

1 APPARENT VISCOSITY MEASUREMENT

1.1 Equipment - Monitorized Nozzle

A customized nozzle (Fig. 1) has been developed with an internal channel of 12 mm diameter and 300 mm length. It has been installed in an Italtech 3000T/WP19800 machine, suitable for large parts injection such us car bumpers, containers and washing machine tubs. The nozzle is equipped with three chain heaters controled by thermocouples to control the temperature of the molten material, and two kistler 4083A sensors for melt pressure and temperature measurement. These transducers are assemblied to their charge amplifiers. The plastication unit is equipped with a wire potenciometer and hydraulic pressure sensor. A complete system of computer, software, acquisition card, signal conditioning, etc. complete the measure chain.

Another nozzle has been simultaneously developed with an internal channel of 3mm thickness, 20 mm width and 100 mm lenght. It has been intalled at a JSW 85EL II machine.

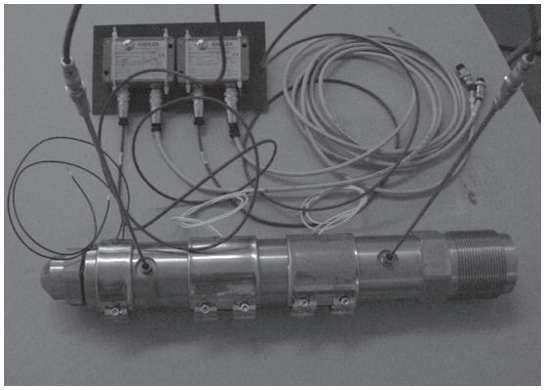

Fig. 1. *Nozzle with sensors for 3000T Machine*

1.2 Apparent Viscosity Measurement - Theory

One of the crytical problems when injecting large parts is to maintain production parameters inside a process window if using large amounts of raw material whose viscous properties can vary between different lots. For this reason it is necessary the use of an apparatus that allows to determine viscous properties during production machine operation [10] to [13] and [15]. In this case the monitorized nozzle is assembled between the plasticating cylinder and the mould the measure the properties of the molten plastic.

The procedure the measure the apparent viscosity consists in make free purges of the cylinder through this nozzle with constant screw speed. Pressure losses and temperatures are measured with the sensors, also screw position is measured with the wire potenciometer. Actual temperature of the molten plastic is also measured with a contact phyrometer placed in the injected mass after each purge. Graph curves like showed in figure 2, and time dependent data were stored in the computer.

The screw speed is a calculation by derivating screw displacement and the flow rate (Q) by multiplying the speed and the cross section of the channel.

Wall shear rate (γ_w), wall shear stress (τ_w) and apparent viscosity (η_{app}) are calculated using this formulae (8), (9) and (14):

$$\dot{\gamma}_w \cong \left(-\frac{dv}{dt}\right)_{r=R} = \frac{4 \cdot Q}{\pi \cdot R^3} \tag{1}$$

$$\tau_w \cong \tau_{rz}(r = R) = \frac{-\Delta P \cdot R}{2 \cdot L} \tag{2}$$

$$\eta_{app} = \frac{\tau_w}{\dot{\gamma}_w} \tag{3}.$$

Where, Q is the channel flow rate, R is the radius of the nozzle channel, ΔP is the difference of measured pressure values in the transducers and L is the distance between transducers.

1.3 Experimental Viscosity Calculation

Six different screw speeds and three different temperatures were programmed and each trial was repeated five times. This calculations are made each purge cycle to obtain one value of apparent viscosity associated to a shear rate and temperature value.

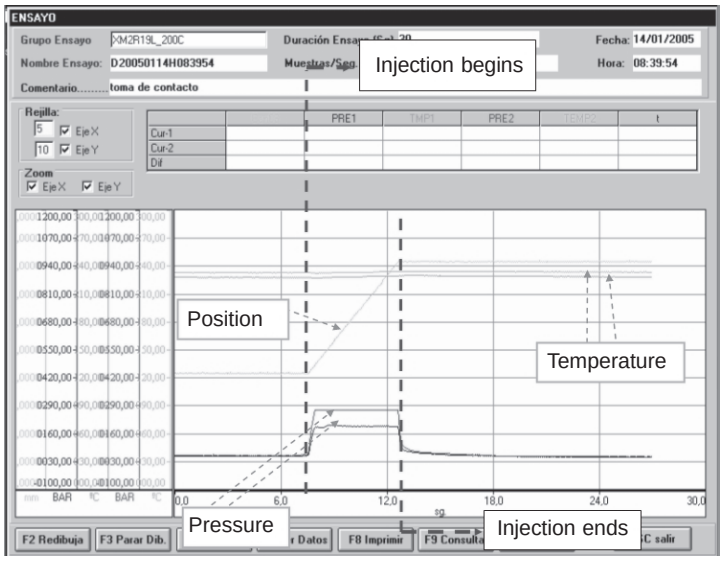

Fig. 2. *Air purge data acquisition*

After a complete test up to 90 results have to be fitted to construct a viscous model.

The results obtained for a 20% Talc filled Polypropilene, Hostacom XM2 R19L, were compared with those found in Moldflow material database and the raw material supplier, Basell, database. Also, the actual lot of material has been characterizated in a Gottfert 1,500 capillary rheometer. The fifth source of material data has been the results obtained from a similar procedure with a sensored nozzle with rectangular cross section operated in a 85Ton electrical machine.

Resultant data have been fitted using Visdat application to calculate Klein model constants for viscosity calculation accordingly to this equation:

$$\ln(\eta) = a_1 + a_2 \ln(\dot{\gamma}) + a_3 T + a_4 [\ln(\dot{\gamma})]^2 + a_5 \ln(\dot{\gamma}) T + a_6 T^2$$

where:

η [Pa·s] represents apparent viscosity,

γ [s^{-1}] represents shear rate,

T [ºC] represents mass temperature,

a_1 ... a_6 are model constants.

The result of data fitting has been complex because of the origin of the measured points that differs roughly from a conventional capillary rheometer. Table 1 shows the selected values at 3 different temperatures (column 1), wide range of calculated shear rate (column 2), measured viscosity (column 3) and calculated viscosity with Klein model after data fitting and six constants a_i calculation (column 4). It has been necessary to filter some information further 6% error from fitted data (column 6) so it can be concluded, the precision of this way of viscosity measurement is less precise than capillary rheometry.

Table 2 summarizes a comparison between calculated constants for Klein model (column 1) from different sources. The coefficients in the

Table 1. *Comparison between measured and fitted data*

Temp. [ºC]	Shear rate [s^{-1}]	Meas. V [Pa·s]	Calc. V [Pa·s]	% error
200	315.97	244.81	244.50	-0.127
200	1014.73	133.00	129.96	-2.338
200	4137.13	47.68	48.40	1.497
200	8174.26	28.93	27.44	-5.452
220	315.27	211.06	211.06	0.000
220	4164.88	45.23	48.15	6.047
240	300.60	208.91	212.19	1.548
240	2037.58	59.10	55.82	-5.881
240	4181.90	28.80	30.02	4.069

Table 2. *Comparison of Klein model constants*

Klein coeff.	Capillar rheometer	Rectangular nozzle	Circular nozzle
a1	7.3077	11.556	11.196
a2	-0.47197	-0.64547	0.83060
a3	1.67471E-02	-1.48095E-02	-5.68294E-02
a4	-2.16310E-02	-2.20278E-02	-6.26514E-02
a5	8.47880E-04	1.0327E-03	-2.88984E-03
a6	-7.08439E-05	6.78162E-06	-1.57621E-04
Standar dev.	6.36E-03	8.5E-03	1.32E-02

second column result after fitting the measured viscosity values obtained for the same lot of raw material using a capillary rheometer.

The third column shows the coefficients obtained using the same raw material and the monitorized nozzle with rectangular cross section. The fourth column shows the coefficients obtained using the nozzle with sensors described in this paper. Tha last row evidences the accuracy of the fitted coeffients in terms of standard deviation below 1.32%. With all this coefficients a complete plot for apparent viscosity can be drawn, and all necesary values of viscosity as a function of shear rate and temperature can be determined for injection moulding simulation.

Different curves representing shear rate influence in viscosity calculation at a temperature of 240ºC are plotted in Figure 3. Calculated Klein models are used for this plots. The differences in the curves are similar at different temperatures (200ºC, 220ºC, 240ºC) and the qualitative tendency is quite similar. The differences are caused mainly for the use of Newtonian model for vicosity calculation that is suitable for capillary rheology but not for thick sections as in the nozzle. This phenomenon has been introduced in previous studies [1] to [7].

The results show how the differences in viscosity values increase with the cross section thickness of the measurement apparatus. In this case, the prediction on viscosity with the 3x20 mm section nozzle is no more than 9.5% higher than with the reometer. The differences measured with the 12 mm section nozzle grow up to 30% higher that with the nozzle at the highest shear rates (> 4.000 s^{-1}). The values coming from the material supplier database are coincident with the rectangular nozzle and evidence differences with those measured in the rheometer that depend on the lot of raw material, quite different from that one tested in the laboratory prior this research work.

2 SHORT SHOT CHARACTERIZATION

2.1 Experimental Work

Short shots are one of the most common defects when injecting large plastic parts. These

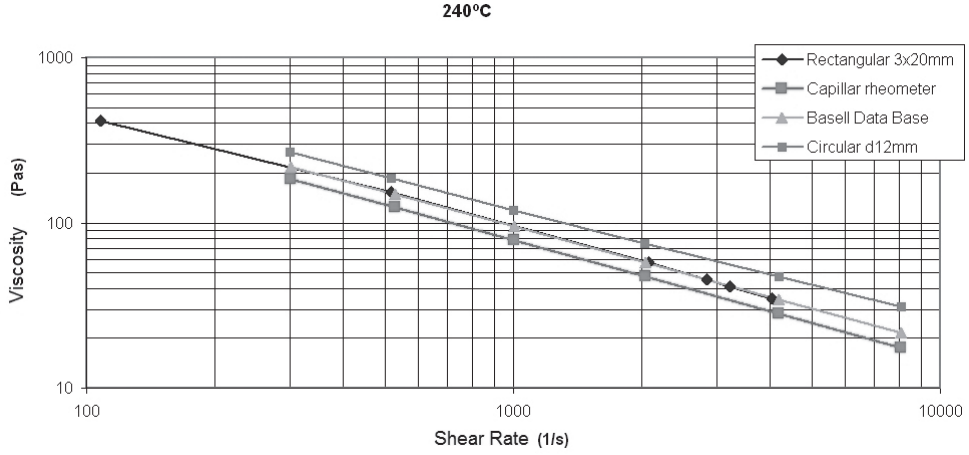

Fig. 3. *Comparison of plots from differen Klein models at 240ºC temperature*

kind of defects are extremely severe because they prove that processing conditions are unstable or unsteady. The result of a short shot implies the refuse of a heavy part of several kilograms weight because of a very small defect of just a few grams. The visual inspection in-line of the produced parts is needed to prevent failed parts are delivered involving additional costs.

A complete parameter registration has been developed up to 2.37 cycles during a test of a mould for washing machine tubs. The monitorized nozzle has been used in combination with the hydraulic pressure transducer of the injection machine and the Statistic Process Control (SPC) of the machine.

It has been proved the productive parameters follow different patterns depending on a raw material lot. For this reason injection parameters must be readjusted periodically because of the viscosity variations, specifically those related to injection and packing phase. The different lots of raw material are certified for production of parts between a range of values of Melt Flow Index so that variations in rheological behaviour of the molden plastics must be assumed in the production lines. It influences the thermal response of the material in terms of heat generated during plastification process by means of viscous heating of the melt. Melt temperature variations induce fails such us short shots as shown in Figure 4. For this reason, the monitorized nozzle is used to check temperature evolution and to control the plastic viscosity monitoring pressure losses between transducers.

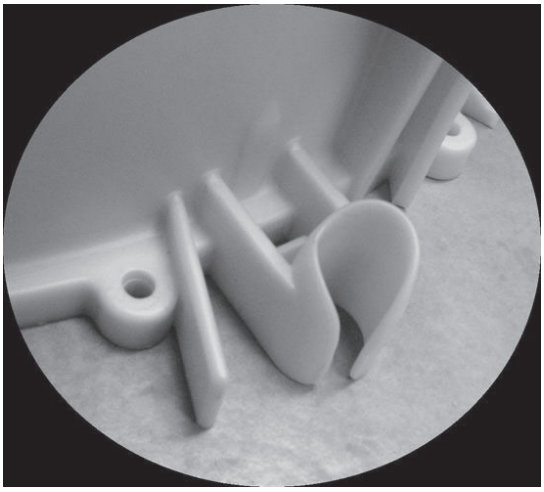

Fig. 4. *Short shot at the end of filled cavity*

Table 2. *Operation parameters and deviations*

Parameter	Part OK	Part NOK	Abs. diff	Rel. diff
Inj. time	6.672	8.188	1.52	22.72
St. dev.	0.033	0.073		
Pack. time	10.424	10.312	0.11	-1.07
St. dev.	0.159	0.082		
Hydr. pres.	176.046	200	23.95	13.6
St. dev.	0.487	0		
Sensor 1 pres.	512	531.7	19.7	3.85
St. dev.	1.225	1.059		
Sensor 2 pres.	863.814	884.627	20.81	2.41
St. dev.	2.455	2.133		
Av. pack. pres.	116.032	115.057	-0.98	-0.84
St. dev.	0.227	1.174		
Nozzle temp	281.661	271.693	-9.968	-3.54
St. dev.	0.071	0.142		
Screw. displ.	353.22	332.17	-21.05	-5.96
St. dev.	0.446	0.819		

Table 2 shows the most relevant parameters when producing these parts. Results for 1.940 parts completely filled (column 2) demonstrate they are produced under stable parameters. The standard deviations are 0.033 for injection time, 0.487 for hydraulic pressure, 0.071 for nozzle temperature and 0.446 for screw displacement. Also measured hydraulic pressure, pressure in both sensors in the nozzle and average hydraulic pressure during packing are quite stable. Results for 430 short shots (column 3) show the effect of viscosity increment with lower mass temperature. The reduction of mass temperature of 9.968 ºC is due to a reduction of viscosity of raw material that reduces roughly the contribution of viscous friction to plastic heating.

Two plots of the registered parameters of correct and failed parts are shown in Figures 5 and 6. These plots show the evolution of several properties through the cycle time. The optimum process shown in Figure 5 is developed under high hydraulic pressure conditions over 190 bar (*PH*). Total volume injected is nearly proportional to screw displacement (*Carr*). Temperature variations in the nozzle during a cycle are neglectable (*T_1* and *T_2*). In Figure 6 it can be observed that melt temperature decreases 3.54% and consecuently nozzle pressure increases. Defects occur when the hydraulic pressure reaches the injection pressure limit (200 bar). From this moment the end of filling phase is delayed (22.72%) because of the reduction of screw speed and a total screw displacement is reduced (5.96%) inducing short shot.

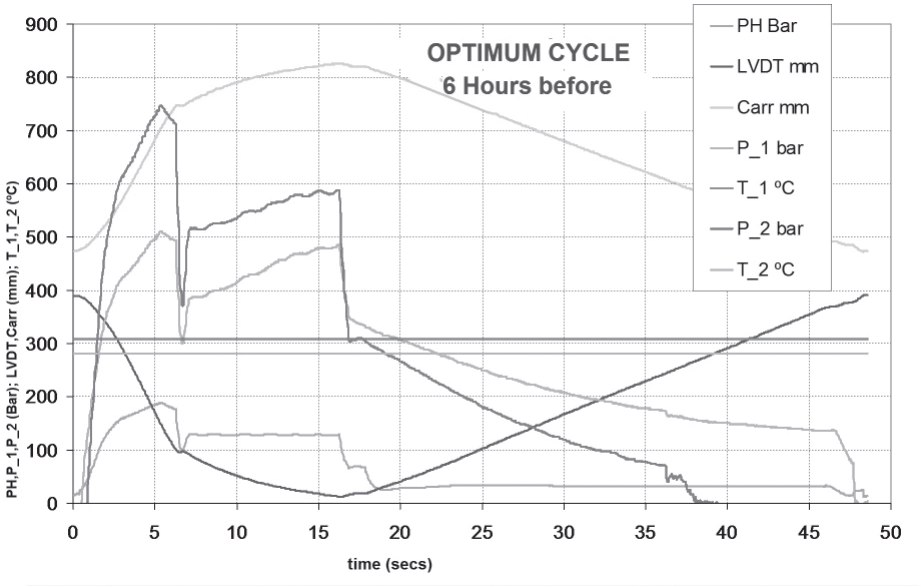

Fig. 5. *Optimum cycle parameters*

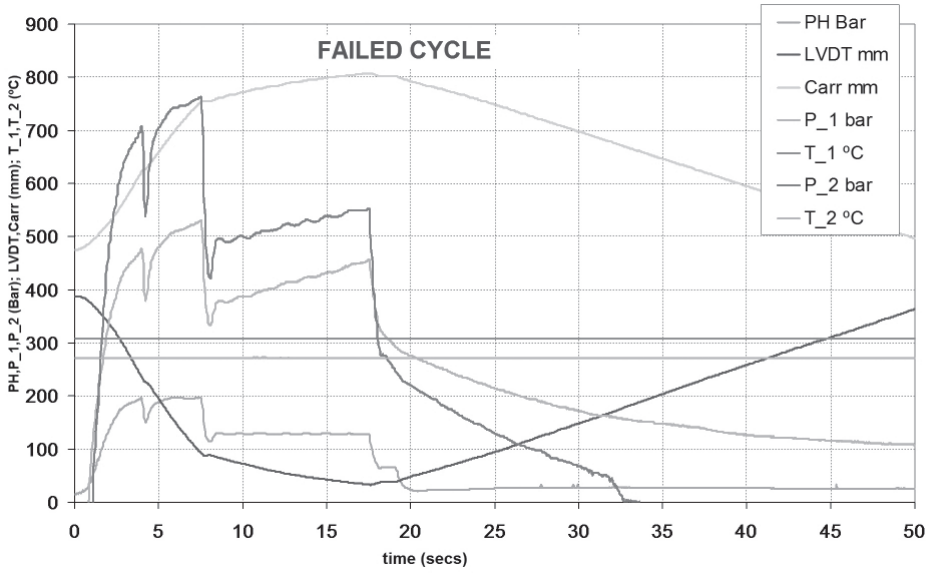

Fig. 6. *Parameters when short shot appears*

2.2 Simulation Work

A complete simulation has been done with Moldflow 5.0 software. Simulations have been developed using measured material viscosity data and measured processing conditions as inputs. A limit of 200 bar in injection pressure has been introduced so, as this limit has been reached the programed injection time has extended up to 18.08 s that fits with the measured time in the machine of 18.5 s.

Results have demonstrated that operation under these conditions increases roughly injection pressure and short shot appears because the slower displacement of the injection screw that stand the flow front to freeze. Figure 7 shows the results of the simulation regarding mould filling. Comparing this image with Figure 4 it can be predicted the exact location of the short shot.

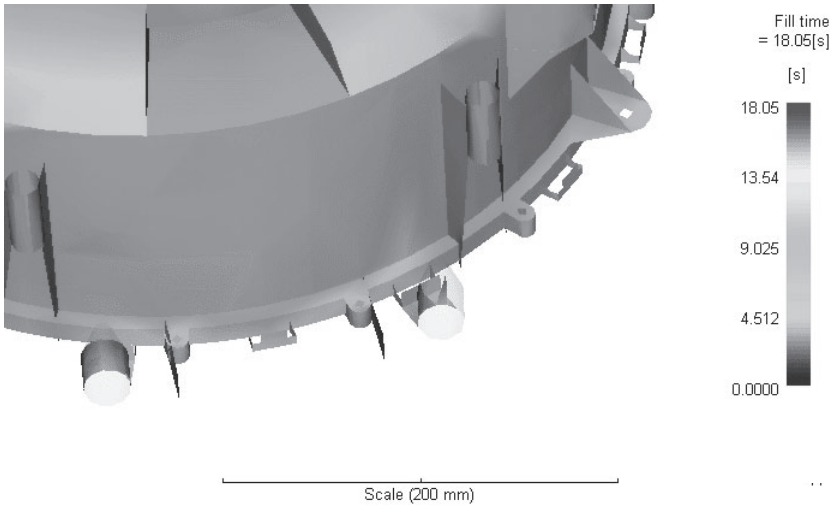

Fig.7. *Short shot simulation*

3 DISCUSION

The use of monitorized nozzle to determine apparent viscosity of molten polymers in an injection moulding machine has been accurate enough to compare results with those obtained from differen sources. But data fitting and construction of Klein model has demonstrated less accuracy than capillary rheometry. This unaccuray grows at high shear rate values due to divergences between the fully developed flow pattern through a capillar and the flow pattern through a thick channel.

Comparisons between results from different sources have demonstrated that as thicker is the cross section greater are the differences between viscosity predictions. Also the calculation of pressure losses when filling thick cavities or runners is less accurate as they are thicker because of the assumptions made for polymer flow modellisation.

The experimental work with large parts evidences that small variations in raw material properties influence process parameters such us pressure and temperature without varying processing conditions, so that, monitoring those parameters with a nozzle with sensors fits to suitable process control.

Graph plots of processing parameters show that short shots could be prevented because they appear as a consecuence of gradual degradation in processing conditions as slow decrease of melt temperature and increment of pressure needed for complete mould filling. This incident occurs after several cycles as different lots of raw materials are still mixed so that an alarm could be installed attached to the monitorized nozzle or temperature conditions could be automatically readjusted.

Concordance between actual filed parts and simulated ones allows to manage the inspection activities of the produced parts easily, revealing the risk zones of them. The results of the simulation have fitted the defects obtained in the experimental work when using the material data generated with the monitorized nozzle better that those available in the database.

A similar work has been developed to prevents fails like flashes (Fig. 8), but results have not been succesful. All these defects have appeared suddenly, without oriented variation in processing parameters. The main reason for this defects has been the temporal obstruction of some of the gate points or hot runners.

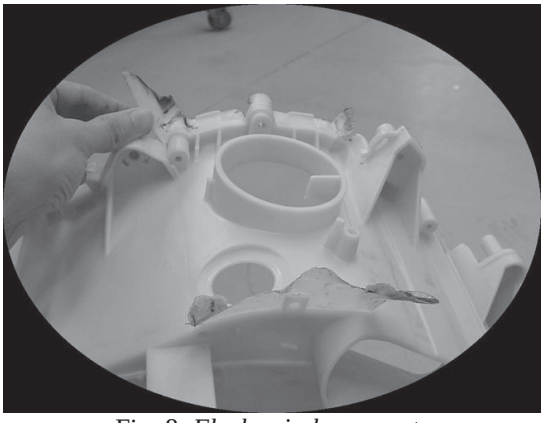

Fig. 8. *Flashes in large parts*

4 CONCLUSIONS

A monitorized nozzle has been used to measure apparent viscosity and calculate Klein model for a talc filled polypropylene. Estimated error increases with the dameter or thickness fo the cross section through the nozzle due to differences in the flow behaviour with capillary rheometer mainly. Several phenomena have been also detected like increments of viscosity up to 20% with higher level of pressure downstream, and viscous heating through the nozzle at high shear rates.

A monitorized nozzle has been used to register injection moulding parameters of thousands of washing machine tubs. Also sets of patterns of operation parameters have been compared in free of defects parts and failed ones. Short shot defect has been characterizated.

The progressive evolution of parameters from good to failed parts allow to establish knowledge based criteria to predict fails such us short sort.

5 REFERENCES

[1] Lee, B.L., White, J.L. *Trans. Soc. Rheol.*, 18, 467 (1974).

[2] Shertzer, C.R., Metzner, A.B. *Trans. Plast. Inst.*, 31, 148 (1963).

[3] Han, C.D. *J. Appl. Polym. Sci*. 14, 1775 (1970).

[4] Ferry, J.D. *Viscoelastic properties of polymers*, 2nd Ed. New York: Wiley, 1970.

[5] Sekiguchi, M. *Chem. High Polym.*, 26(295), 721 (1969).

[6] Mendelson, R.A., Finger, F.L. *J. Appl. Polm. Sci.*, 17, 797 (1973).

[7] Bagley, E.B., Duffey, H.J. *Trans. Soc. Rheol*., 14, 454 (1970).

[8] Han, C.D. *Rheology in polymer processing*. London: Academia Press, 1976.

[9] Cogswell, F.N. *Polymer melt reology*. London: George Goodwin Limited, 1981.

[10] Mercado, D. *Comparison of different methodologies to determine rheological curves of polypropylene*, Ph.D. thesis. University of Zaragoza, 2003. (In Spanish).

[11] Fernandez, A., et al. Criteria on feeding system design: convencional and sequential injection moulding. *Journal of materials processing technology*, 171 (2006), p. 373-384.

[12] Fernandez, A., et al. Influence of ther recycled material percentage on the rheological behaviour of thermoplastic material in injection moulding process. *Waste Management*, 27 (2007), p. 656-663.

[13] Serraller, F. *Collection and analysis of filling parameters of an spiral mould with ABS to be applied on industrial molded parts*, Ph.D. thesis. University of Zaragoza, 1995. (In Spanish).

[14] Javierre, C., Claveria, I., Ponz, L. Method for generation of rheological model to characterize non-conventional injection molding by means of spiral mould. *Journal of Materials Processing Technology*, 162-163 (2005), p. 477-483.

[15] Javierre, C., Aisa, J., de la Serna, J.A. An example of simulation tools use for large injection moulds desing: The Contenur 2400 l. solid waste container. *Journal of Materials Processing Technology*, 175 (2006), p. 15-19.