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Part mass and shrinkage in micro injection moulding: statistical based optimisation using multiple quality criteria

Daniele Annicchiarico *, Usama M. Attia[1] and Jeffrey R. Alcock[2]

* Building 56, Cranfield University, Wharley End, Cranfield, Bedfordshire, MK43 0AL, UK. E-mail: *d.annicchiarico@cranfield.ac.uk*

1 Manufacturing Technology Centre Ltd., Ansty Business Park, Pilot Way, Coventry, CV7 9JU, UK. E-mail: *usama.attia@the-mtc.org*

2 Building 50, Cranfield University, Wharley End, Cranfield, Bedfordshire, MK43 0AL, UK. E-mail: *j.r.alcock@cranfield.ac.uk*

Abstract

Purpose: The aim of this paper is to optimise process conditions in micro injection moulding (μ–IM) to minimise shrinkage whilst maximising part mass. *Method:* A Design of Experiment (DoE) approach was implemented for studying the effect of five processing parameters on shrinkage and part mass. A multiple quality criteria based analysis was used to optimise the process. *Results:* Significant factors were found for shrinkage and part mass. *Conclusions:* The multi quality criteria could be optimized, and this optimization validated experimentally.

Keywords: Part mass; shrinkage; micro injection moulding; optimization; multiple quality criteria

1. Introduction

1.1 Purpose of paper

Injection moulding literature indicates that part mass has an important role in shrinkage, where shrinkage is reduced when part mass is maximized (without overfilling behaviors such as the production of “flash”) [1]. However, it is difficult to use part mass as a factor in an experiment, as it is not a variable that is easy to control independently (unlike, for example, mould temperature). It may also be affected by the same factors that influence shrinkage.

In a previous study, metering size was used as a factor (and part mass as a response) [2]. However, two issues act to reduce the usefulness of metering size as a factor. Firstly its accuracy. The metering size accuracy of a dedicated micro-moulder (Battenfeld 50) – as used here – has been estimated at 20 mm^3 [2] (as against total moulded part size of 150 mm^3). Secondly, the variation of metering size volume with polymer temperature [3].

In order to use part mass data to attempt to optimise shrinkage, the present study proposes a multiple quality criteria method, i.e. it attempts to optimise for both the minimum total shrinkage and the maximum part mass, because of the known effect of one factor on the other. Shrinkage itself is measured by a recently proposed and demonstrated methodology for the study of the effects of injection moulding parameters on shrinkage behaviour at the micro-scale [4].

As optimisation of total shrinkage would be particularly hard to achieve for polymers which show anisotropic shrinkage behaviour, an example of such a polymer (a grade of polyoxymethylene) was chosen for this study [5].

1.2 Adoption of part mass as a parameter at the micro-scale

In the literature, few papers have adopted part mass as the experimental response in micro-parts. Ong et al. [5] analysed parameters affecting the mass of micro-parts using a Design of Experiment methodology. Mould temperature was the most significant factor affecting part mass; maximum part mass was associated with increasing mould temperature, injection rate and injection pressure.

Attia et al. [6] considered part mass as output parameter. The five processing parameters investigated were melt temperature, mould temperature, injection speed, holding pressure and cooling time. Desirability functions were considered for improving the quality filling.

Zhao et al. [2] studied specimen quality in terms of metering accuracy and homogeneity: part weight and gear diameter of moulded micro parts were measured as experiment responses. The statistical analysis identified the metering size (defined as the volume of material injected in the cavity mould) and the holding pressure as the most critical factors that affected the part weight and the diameter of micro part moulded.

1.3 Multiple quality criteria optimisation

Attia et al. [7] used the similar approach to that adopted in the present paper for the investigation of the effect of processing parameters on two quality criteria: part mass and the variability of part mass. Desirability functions were successfully implemented to predict the processing conditions that fulfilled the requests to maximise both criteria. The final results were validated experimentally for demonstrating the reliability of this approach.

Bellantone et al. [8] have recently adopted a similar approach.

2. Methodology

2.1 Material and equipment

The material analysed in this paper was a semi-crystalline polymer, polyoxymethylene (POM), from BASF (Ultraform® W2320 003) [9] (melting point 166°C, tensile strength at room temperature 65MPa, linear thermal expansion coef. 0.6E-4 mm mm^{-1} C^{-1}).

Mould manufacture was realized using a KERN Evo five-axis micromilling machine for ultra-precision machining, with a workpiece precision of 1 μm and final surface quality of 0.1 μm. The micro injection moulding machine used was a Battenfeld Microsystem® 50. The specimen dimensional measurement was conducted using the optical system TESA Visio 300, with an accuracy of ±1 μm. Part mass was measured using an analytical scale with accuracy of ±1 mg.

2.2 Detecting influential processing conditions for shrinkage

The statistical design was adopted from Annicchiarico et al. [4].

Table 1 reports the processing parameters analysed in the present paper. Initial values were determined during a familiarisation stage, where trial and error experiments were conducted to specify the experimentation window of the process. The screening stage allowed the identification of the high (+) and low (-) ranges. The higher (+) limits were obtained by increasing the initial values indicated in Table 1 until excess "flash", started to be notable. The lower (-) limit was obtained by decreasing the values gradually until defects started to appear, for example, incomplete filling or poor edge definition.

Table 2 reports the statistical model adopted, which is based on a half fractional factorial design. It shows the runs used during the injection moulding stage.

For each combination of processing parameters, the shrinkage of five specimens moulded cyclically (continuously) were measured according to the standard procedure reported in [10]. Figure 1 shows an example of a moulded POM specimen. During the moulding process, other moulding conditions are kept constant: cooling time: 17 s; metering volume: 210 mm^3; injection speed: 250 mm s^{-1}.

2.3 Optimising multiple quality criteria using desirability functions

The optimization used here follows the statistical method outlined in [7].

The method applied in this work implements desirability functions [11]. Desirability functions were used to predict a combination of processing parameters that fulfilled two quality requirements. Each response y_i was individually converted into a desirability function d_i that translates each effect between 0 (the effect of the process are out of target and

unacceptable) and 1 (the effects are relevant to the target value or range). The individual d_i were combined in the overall desirability, D, where $D= (d_1 \times d_2 \times d_m)^{1/m}$ and m is the number of responses: also D has a range between 0 and 1, and had to be maximized; the values 0 and 1 had the same meaning of those reported for d_i.

In this work the goal was to maximize part mass and minimize total shrinkage. The individual functions for meeting these requirements were represented in Equation 1 and Equation 2, respectively.

Equation 1

$$d_{1=} \begin{cases} 0 & y < L \\ \left(\frac{y-L}{T-L}\right)^r & L \leq y \leq T \\ 1 & y > T \end{cases}$$

Equation 2

$$d_{2=} \begin{cases} 1 & y < T \\ \left(\frac{y-U}{T-U}\right)^r & T \leq y \leq U \\ 0 & y > U \end{cases}$$

In both equations, U and L were the upper and lower limits, y was the response, T was the target and r values were the function weight (linear or non-linear), which in this case were all set to be equal to 1. Shrinkage minimisation and part mass maximisation requires setting upper and lower limits selected using the results reported in Table 3. The shrinkage target was the medium-low value between the specimens with low S_T: the target value was set to 3.5% and the upper limit was 4%. Mass target value was chosen as the value closer to the highest part mass moulded (the specimen moulded with the 16th run). The part mass target value was 49.5 mg and the low limit was 48 mg. In the optimisation stage, the individual desirability function d_i and overall desirability D were maximised and set equal to 1.

2.4 Methodology for measurements

For determining shrinkage, the procedure was adopted from Annicchiarico et al.[4] Specimens were moulded by manufacturing a micro-mould following the micro-scale requirements of ISO 294-3 [12] square mould design. The dimensions were adapted to test micro-scale features. The final dimensions of the single square cavity were length= 9.987±0.001 mm, width= 9.980±0.001 mm, thickness=0.350±0.001 mm.

Five specimens were chosen, after the injection machine operated for a number of uninterrupted cycles (Table 1 reports the processing parameters tested) to reach stable operation conditions, such that random errors were minimised.
The conversion of dimensional variations in total shrinkage values - defined as the difference in dimensions between a test specimen after 24 hours and the mould cavity in which it was moulded - was implemented as specified in of ISO 294-4.
Part mass was determined by weighing the same five specimens used for shrinkage measurements with an analytical scale.

2.5 Data representation

The statistical analyses were conducted using Pareto charts, main effect plots and interaction plots. Minitab 16 [13] was used to process the data. The processing parameters were labeled as A (hold time), B (hold pressure), C (injection pressure), D (mould temperature) and E (melt temperature). The combined influence of two of these parameters was described by combining the two corresponding letters.

Pareto charts were used for determining the statistical significance of the processing parameters. The chart reports the absolute value of the effects and draws a reference line on the chart. The vertical line represents the alpha (α) value, which was the maximum acceptable level of risk. Alpha was expressed as a probability, ranging between 0 and 1. During the statistical study, the α value was set at 0.05. This statistically means that the possibility of finding an effect that does not really exist was 5%.

The main effects plot permitted the identification of the response of the single critical process parameters (previously identified by Pareto chart) in terms of direction and magnitude: the larger the slope of the line, the larger the significance of the respective processing parameter; a positive slope indicates a direct relationship and a negative one indicates an inverse relationship with the factor analysed.

The interaction plot identified the response of the combined critical processes. An interaction was present when the change in the response from the low to the high level of a factor depended on the level of a second factor. If the lines were parallel to each other or did not intersect, there was no interaction present within the investigated process window. The greater the departure of the lines from the parallel state, the higher the degree of interaction.

3. Results

3.1 Measurement results

Table 3 reports part mass (W) and total shrinkages (S_T) values in parallel to (p) and normal to (n) the flow direction. Part mass values shown in Table 3 include both the specimen and the attached gate masses. This was done because separating the gate from the specimen caused profile damage that affected shrinkage measurements. Gate mass was estimated to contribute to about 2% of total part mass (1.10±0.03 mg gate mass).

Table 4 reports the lowest (Low) and the average (Av) values for total shrinkage (S_T), on parallel to (p), and normal to (n), the flow direction.

3.2 Critical factors that affect shrinkage

Figure 2 reports the Pareto chart of total shrinkage in parallel to the flow direction. Three single factors had statistically significant effects on shrinkage: mould temperature D, hold pressure B and melt temperature E. In addition, two combinations of factors had statistically significance: hold pressure with mould temperature BD, and mould temperature with melt temperature DE.

Figure 3 shows the corresponding main effects plot for the single critical factors. The figure shows that mould temperature magnitude is larger than hold pressure and melt temperature. The slopes of the parameters indicate that an increase in these parameters leads to a decrease in shrinkage.

The plot of Figure 4 represents the interaction between holding pressure and mould temperature (labelled as BD in Figure 2). The boxes show the change of total shrinkage, in parallel to the flow direction S_{Tp}, with both mould temperature and hold pressure. The top right box plots shrinkage as a function of mould temperature, the bottom left box plots shrinkage as a function of hold pressure.

Considering mould temperature (top right), the decrease of total shrinkage in parallel to the flow direction S_{Tp} moving from the low (85°C) to the high (115°C) temperature is larger when hold pressure is low (450 bar) than when it is high (550 bar). Considering hold pressure (bottom left), the decrease of S_{Tp} moving from the low (450 bar) to the high (550 bar) pressure is larger when mould temperature is low (85°C) than when it is high (115°C).

Figure 5 represents the interaction between melt and mould temperatures (labelled as DE in Figure 2). The boxes show the change of total shrinkage, in parallel to the flow direction S_{Tp}, with both mould temperature and melt temperature. The top right box plots shrinkage as a function of melt temperature, the bottom left box plots shrinkage as a function of mould temperature.

Considering mould temperature (top right box), the decrease of total shrinkage in parallel to the flow direction S_{Tp} as we move from the low (85°C) to the high (115°C) temperature is larger when melt temperature is low (190°C) than when it is high (200°C). Considering melt temperature (bottom left box), the decrease of S_{Tp} moving from the low (190°C) to the high (200°C) temperature is larger when mould temperature is low (85°C) than when is high (115°C).

In contrast to the above, no statistically significant effects of factors were seen for shrinkage normal to the flow direction.

3.3 Critical factors that affect part mass

Using the same statistical tools used for total shrinkage, the critical factors that affect part mass were analysed. Figure 6 and Figure 7 represent the Pareto chart and the main effects chart of the POM specimen part mass. The Pareto chart in Figure 6 shows that in terms of part mass, the statistically significant process parameters were mould temperature D, hold pressure B and melt temperature E.

The main effects plot, shown in Figure 7, reports how changing each process parameter between the low and high values affects the actual magnitude of specimen mass. The slopes of the three significant parameters, identified from the Pareto chart, are all positive in the main effects chart, which means that an increase in specimen mass is directly related to each of the three parameters.

3.4 Optimisation step

Table 5 summarises the critical factors observed for shrinkage and part mass.

The optimisation stage identified the optimum combination of parameters that minimised shrinkage and maximised the part mass. These are shown in Table 6.

Specimens were moulded for experimental validation. Table 6 reports their shrinkage and part mass. These results can be compared with those reported in Table 4. Table 7 summarise this comparison.

In Table 7, the actual average, low and optimised values of shrinkage and weight are given in parentheses, the optimised in the first row of data and the actual and average in the first column of data. The body of the table compares the optimised with the non-optimised values as a percentage change. The first set of three rows compares against average values from prior experiment. The second set of three rows compare against the best values (lowest

shrinkage or mass) from prior experiment. A negative value in the table indicates a reduction in shrinkage or part mass.

Figure 8 reports the mass distribution of the specimens relative to different process parameters. The x-axis shows the run numbers 1 to 16 as reported in Table 3. Run number 17 is for the optimised process parameters as shown in Table 6. The y-axis shows the resulting specimen mass expressed in milligrams. In Figure 8 the white bars indicate mass values for specimens moulded with processing parameter combinations that include low mould temperature (85°C), while the grey bars refer to mass values resulting from processing parameter combinations involving high mould temperature (115°C). The 17^{th} bar is the part mass of the optimised specimen. Error bars are the standard deviation of five specimens.

4. Discussion

The numerical results reported in Table 3 confirmed the general shrinkage trend reported in the literature [14; 15]: shrinkage in parallel to the flow direction is larger than that normal to the flow direction.

The critical factors that affect total shrinkage and part mass were summarized in Table 5. Temperatures (mould and melt) and holding pressure were identified as single critical factors that affected both shrinkage and part mass. The combinations of each of holding pressure/mould temperature and melt temperature/mould temperature affect total shrinkage in parallel to the flow direction. No critical parameters were found for total shrinkage in normal to the flow direction.

With regard to part mass, the results of this work are in agreement with those of Ong et al. [5], which identified mould temperature as a critical factor for part mass in the same grade of POM. In terms of part weight, Zhao [2] found that the holding pressure has a critical influence (for POM grade Iupitala F20-0).

The effect of optimisation using multiple quality criteria was shown in Table 7. Comparing the numerical results after the optimisation with those before the optimisation (both average and low values), it was possible to evaluate that shrinkage in parallel to the flow direction was reduced (-34% with respect to the average value, -8% with respect to the best shrinkage value). Shrinkage reduction in parallel to the flow direction seems to be balanced by a slight increase in shrinkage in normal to the flow direction (+9.2% with respect to the average value, +40% with respect to the best shrinkage value). The optimised part mass shows a +3% change with respect to the average part mass and a -0.1% change with respect the best

(highest) part mass value. Such a reduction in part mass with respect the best target value does not produce negative effects in terms of incomplete filling or low edge definition. The optimised values are the results of a compromise between shrinkage minimisation and part mass maximisation.

Figure 8 confirmed the critical influence of mould temperature (critical factor both for shrinkage and part mass) highlighted by the statistical study: the relatively short white bars indicate mass values for specimens moulded low mould temperature (85 °C, as shown in Table 2). The longer grey bars refer to specimens moulded with high mould temperature (115°C). The 17^{th} bar is the weight of the optimised specimen. Although the specimen moulded with the optimised parameter does not show a higher value of mass, it exhibits a shrinkage which is more balanced in parallel to, and normal to, the flow direction (3.37% and 3.31% respectively) compared to shrinkages reported in Table 3.

5. Conclusions

This paper implemented a statistical methodology in order to attempt to optimise for both shrinkage and part mass in micro-injection moulding. Five factors were investigated: the injection pressure, the holding pressure, the melt temperature, the mould temperature and the holding time. The temperatures (mould and melt) and the hold pressure were identified as significant factors that affected both shrinkage in parallel to the flow direction and part mass independently. In addition, shrinkage in parallel to the flow direction is affected by combined effect of holding pressure-mould temperature and melt temperature-mould temperature. No critical parameters affected shrinkage in normal to the flow direction. Optimal conditions for the minimisation of the total shrinkage and maximisation of part mass were determined using desirability functions. These conditions were tested experimentally. Measurements verified the reduction in shrinkage and the increase of part mass.

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Processing Parameters	Initial Values	Value +	Value -
Injection pressure [bar]	850	900	800
Holding pressure [bar]	500	550	450
Melt temperature [°C]	195	200	190
Mould temperature [°C]	100	115	85
Holding time [s]	3	4	2

Table 1. POM processing parameters.

Processing parameter combinations						Half fractional factorial matrix				
Run	Hold time [s]	Hold press. [bar]	Inj. press. [bar]	Mould temp. [°C]	Melt temp. [°C]	Hold time	Hold press	Inj. Press	Mould temp	Melt temp
1	2	450	900	85	190	+	-	+	-	+
2	4	450	900	85	200	+	-	-	+	+
3	4	550	800	85	200	+	+	-	-	+
4	4	550	900	85	190	+	-	-	-	-
5	2	550	800	115	190	+	+	+	-	-
6	2	550	900	85	200	-	-	+	-	-
7	2	550	800	85	190	+	-	+	+	-
8	4	450	900	115	190	-	+	+	-	+
9	2	450	800	85	200	-	+	-	+	+
10	4	450	800	85	190	-	-	+	+	+
11	2	450	900	115	200	+	+	-	+	-
12	4	550	800	115	190	+	+	+	+	+
13	2	550	900	115	190	-	+	-	-	-
14	4	450	800	115	200	-	+	+	+	-
15	4	550	900	115	200	-	-	-	-	+
16	2	550	800	115	200	-	+	-	+	-

Table 2. Matrix of half fractional factorial design and processing values.

Run	W [mg]	S_{Tp} [%]	S_{Tn} [%]
1	46.73±0.39	7.649±0.008	2.797±0.007
2	46.98±0.23	6.664±0.001	2.909±0.001
3	47.64±0.33	5.108±0.004	2.890±0.001
4	47.50±0.52	6.092±0.009	2.802±0.002
5	48.19±0.44	3.887±0.002	3.217±0.001
6	47.60±0.38	4.972±0.009	2.923±0.001
7	46.93±0.31	6.775±0.007	2.820±0.001
8	48.23±0.12	3.728±0.001	3.253±0.001
9	46.57±0.18	6.968±0.004	3.388±0.009
10	46.09±0.44	7.954±0.010	2.350±0.008
11	49.32±0.13	3.670±0.001	3.096±0.001
12	48.99±0.03	3.683±0.001	3.155±0.001

13	49.15±0.08	3.629±0.001	3.177±0.001
14	48.73±0.19	3.640±0.001	3.297±0.002
15	49.42±0.06	3.373±0.001	3.306±0.004
16	49.73±0.12	3.633±0.002	3.030±0.001

Table 3. Specimen mass results (W) and total shrinkage (S_T) parallel to (p), and normal to (n), flow direction.

$S_{Tp\ Low}$ [%]	$S_{Tp\ Av}$ [%]	$S_{Tn\ Low}$ [%]	$S_{Tn\ Av}$ [%]
3.63±0.01	5.09±1.66	2.35±0.01	3.03±0.26

Table 4. Lowest and average values for total shrinkage.

	Parallel to flow	**Normal to flow**
S_T	Mould temperature Hold pressure Mould temperature and hold pressure Melt temperature Mould temperature and melt temperature	None
W	Mould temperature, hold pressure, melt temperature	

Table 5. Critical processing parameters.

Hold t [s]	Hold P [bar]	Inj. P [bar]	Mould T [°C]	Melt T [°C]	S_{Tp} [%]	S_{Tn} [%]	W [mg]
4	550	800	115	200	3.352±0.001	3.298±0.004	49.42±0.08

Table 6. Optimized parameters with total shrinkage and part mass results.

		$S_{Tp\ Optim}$ [%] (3.35)	$S_{Tn\ Optim}$ [%] (3.30)	W_{Optim} [mg] (49.42)
$S_{Tp\ Av}$ [%]	(5.09)	-34%		
$S_{Tn\ Av}$ [%]	(3.03)		+9.2%	
W_{Av} [mg]	(47.98)			+3%
$S_{Tp\ Low}$ [%] (13^{rd} run)	(3.63)	-8%		
$S_{Tn\ Low}$ [%] (10^{th} run)	(2.35)		+40%	
W_{Low} [mg] (16^{th} run)	(49.73)			-0.1%

Table 7. Optimization stage effect.

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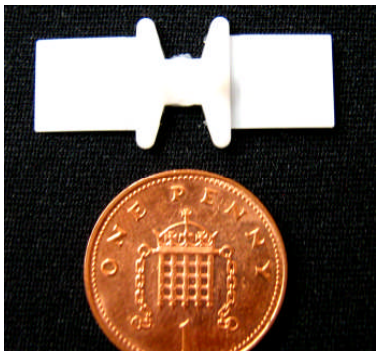

Figure 1. POM moulded specimen.

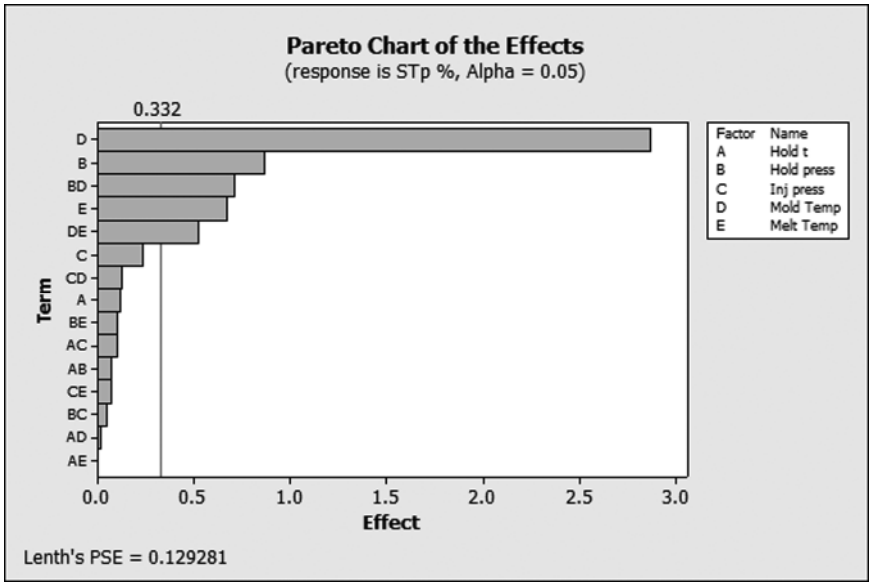

Figure 2. Pareto chart of total shrinkage in parallel to the flow direction.

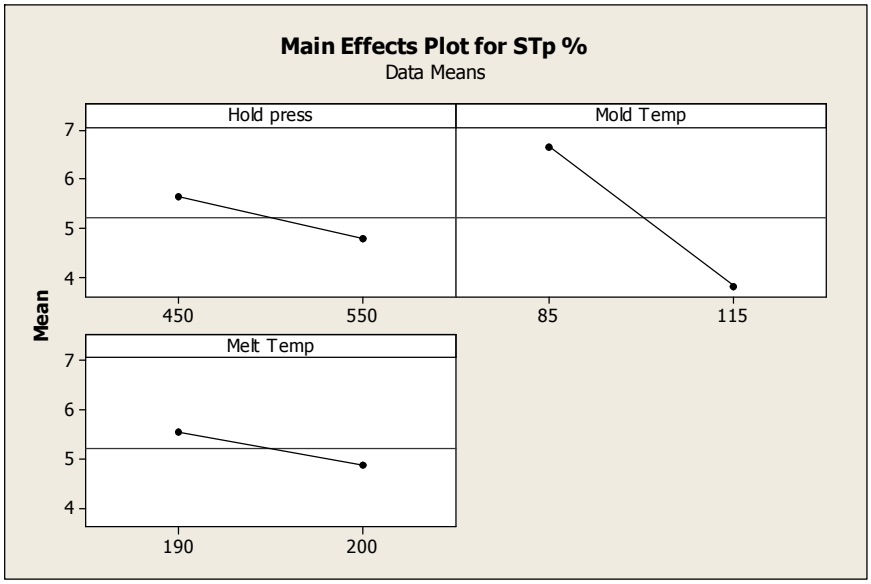

Figure 3. Main effects of total shrinkage in parallel to the flow direction.

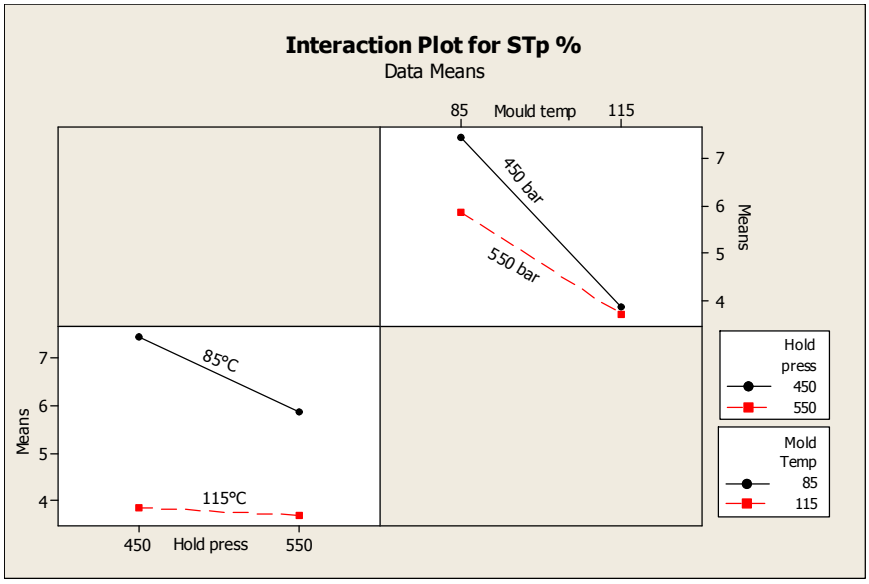

Figure 4. Interaction plot between holding pressure and mould temperature, in parallel to the flow direction.

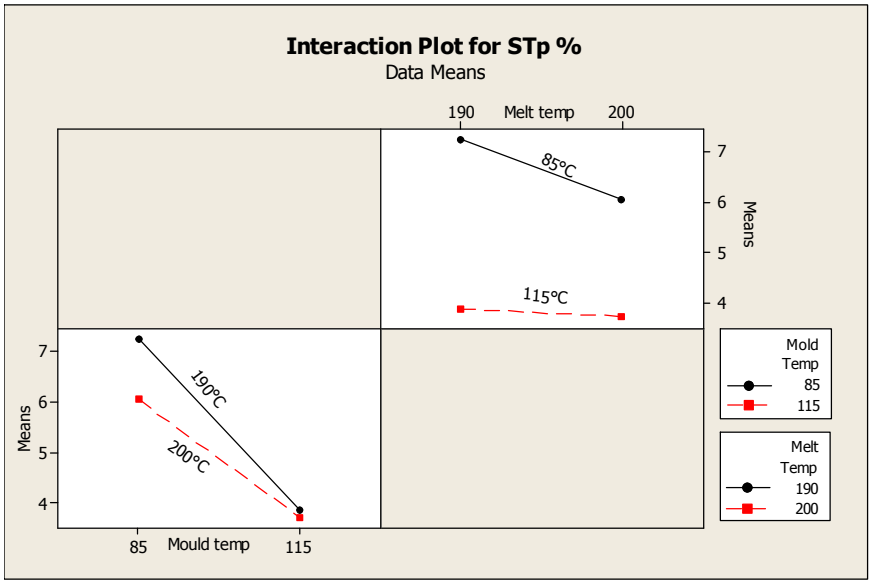

Figure 5. Interaction plot between melt and mould temperature, in parallel to the flow direction.

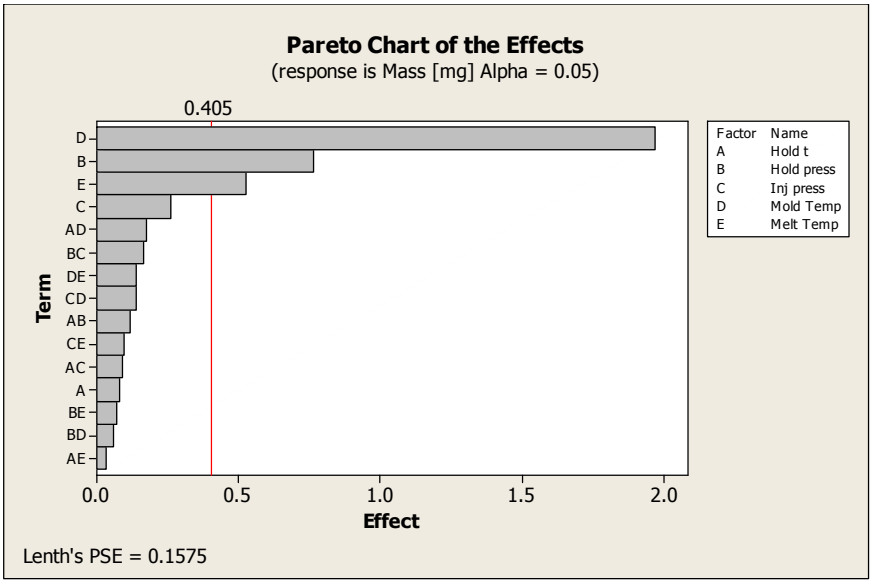

Figure 6. Pareto chart of specimen part mass.

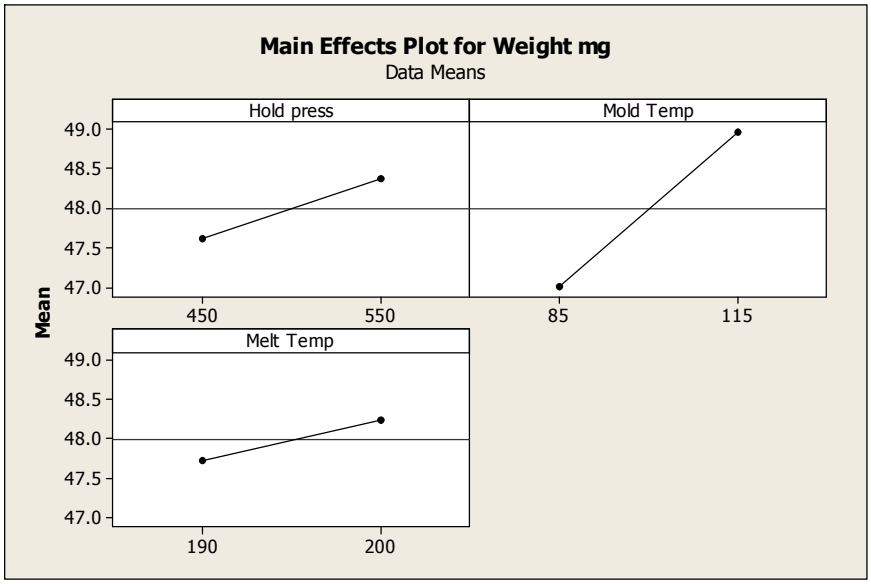

Figure 7. Main effects plot of specimen part mass.

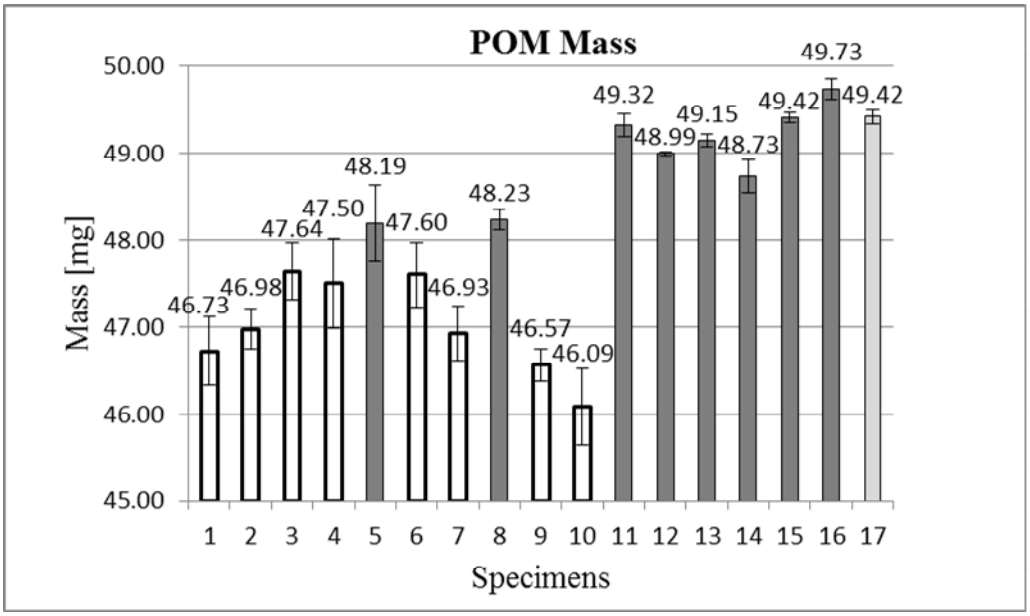

Figure 8. POM part mass distribution.

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Annicchiarico, Daniele

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