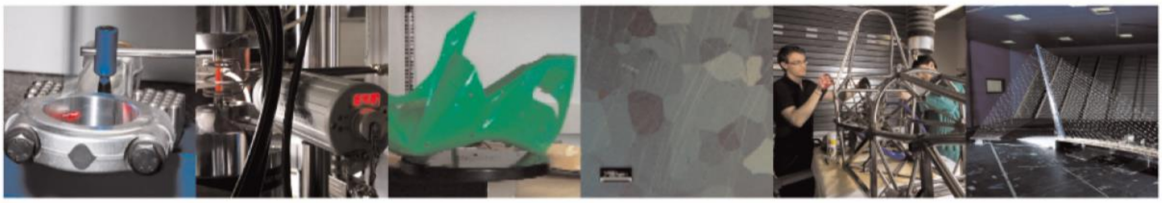

Optimizing process parameters in micro injection moulding considering the part weight and probability of flash formation

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Title: Optimizing process parameters in micro injection moulding considering the part weight and probability of flash formation

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Abstract

This paper proposes an experimental procedure for selecting the optimal processing parameters in micro injection moulding considering two quality features: flash formation and weight of the component. According to a Central Composite Design (CCD), five process parameters (melting temperature, holding pressure, molding temperature, injection speed, and holding time) were varied according to a Central Composite Design (CCD). Empirical regression equations were estimated based on the experimental results to determine the significant factors and the optimal processing conditions. Melting temperature, holding pressure, molding temperature, and injection speed influence the probability of flash formation, as all these factors also increase the probability of flash formation increases. As melting temperature and holding pressure increase, the part weight increases. The selection of the optimal process parameters is performed using a utility function that maximizes the part weight penalized by the probability of flash formation. The utility function suggests selecting low values of molding temperature, injection speed and holding time, and high melting temperature and holding pressure.

Keywords: microinjection moulding; CCD; POM; process parameters optimization

1. Introduction

Micro injection moulding (µIM) is a micro-fabrication technology dedicated to the mass production of micro components. According to Sha et al. [1], µIM can be divided into small components with microfeatures and small components with a weight in the range of hundreds of milligrams. The micro injection moulding process finds application in different fields, such as aerospace, microfluidic, biomedical, and automotive [2]. These applications require the production of high-quality related to the complete filling of the cavity.

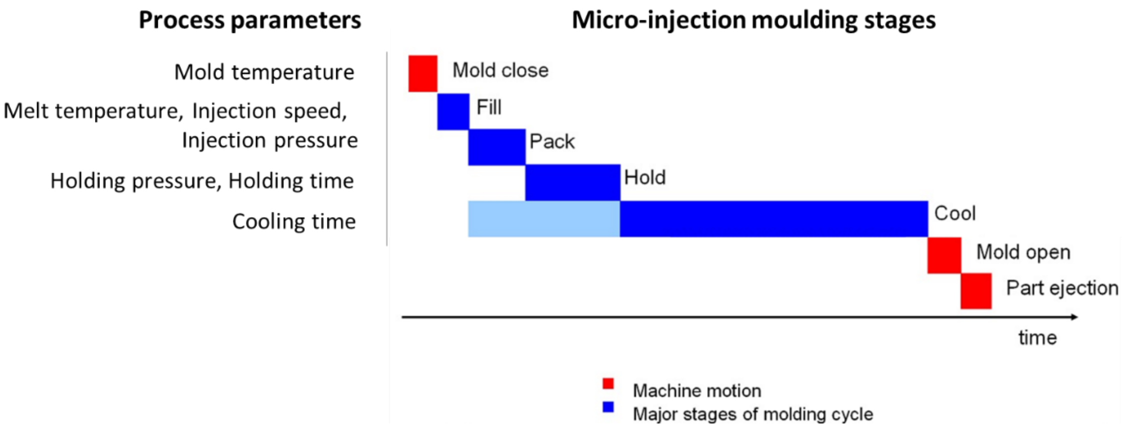


Figure 1. Micro injection moulding stages and main process parameters.

The µIM process is faster than the standard injection moulding process to prevent rapid solidification of the molten polymer caused by the high heat transfer rate. The stages of µIM and the relative process parameters are illustrated in Figure 1. Initially, the mould is closed by the clamping unit that pushes the mould plates tight together while the material is injected (filling phase). Additional material is injected into the cavity during the packing stage to account for shrinkage and backflow. The material is held in the cavity during the holding stage by applying constant pressure until the cooling phase begins. When the cooling is completed, the mould is opened, and the part is ejected. The fast dynamic of the process and the high aspect ratio of the cavities tend to disperse heat very quickly, and therefore the stages might be merged or even bypassed. For example, the polymer cool down could start at the end of the filling phase (light blue bar in Figure 1) due to the fast heat exchange with the mould, reducing the time for the packing and holding stages so that both stages act at the same time.

Investigating the process conditions that ensure a successful filling phase is complicated as different technological and physical aspects must be optimized simultaneously.

The fast cooling of the microcavity due to its reduced size compared to the entire master mould [3] and the different viscous behavior of the molten polymer [4,5] significantly affect the filling phase and, therefore, the quality of the final part. In detail, the viscous behavior is related to the high aspect ratio of the µIM cavity resulting in thermal diffusivity and wall-slip phenomena that alter the polymer's apparent fluid-phase viscosity [6,7].

Different aspects describe the quality of µIM parts: particular, filling pattern [8], cavity pressure distribution [9], and the part weight [10–13]; all these aspects influence the filling phase and the formation defects. The filling pattern strongly affects the holding phase resulting in over-packing or short shot effects. The over-packing effect occurs when extra material is injected into the cavity; on the opposite, the impact of the short shots refers to a lack of material. In the case of over-packing, demoulding becomes unstable with the risk of damaging the component [14,15]. The pressure distribution analysis in the cavities showed that relatively high injection pressures are needed to contrast the excessive pressure drop detected in cavities due to their high aspect ratio [16]. However, in some cases, the combination of the parameters necessary for the complete filling of the cavity leads to an excessive clamping force resulting in the production of flash, a widespread defect in micro injection moulding that is difficult to reduce [13]. Here we propose a literature review on the influence of process parameters on part weight and flash in µIM is carried out.

1.1 Part weight

From the literature, it emerged that the weight of µIM parts could be the element of synthesis for rapid feedback on the quality and reliability of the process. Part weight is a proxy of the filling quality since the weight is maximized when the cavity is properly filled.

Furthermore, measuring the weight of the micro-component is easy to achieve in a real-time production environment at the end of each cycle. It would allow operators to monitor the process automatically.

Few articles focused their research on analyzing the part weight in the micro injection moulding process. The approach typically used in the literature is an experimental plan based on the design of experiments techniques to make a preliminary screening of the process parameters and find a model that correlates the process parameters with the part weight. Then, an optimization approach is used to identify the optimal processing condition that maximizes the quality of the filling, that is, the weight of the part.

For the first time, Attia et al. [17] introduced the part weight as an output parameter to reflect the filling of five separate parts with different micro-feature designs moulded with Polymethylmethacrylate (PMMA). Five processing parameters, namely mould temperature, melt temperature, injection speed, holding pressure, and cooling time was investigated using a screening half-factorial experimentation plan to determine their possible effect on the filling quality. The results show a significant impact of holding pressure for all five parts. After the screening stage, the optimization was carried out to calculate optimum values of the process parameters. A comparison of desirable moulding parameters for different part geometries showed the influence of geometry on processing conditions.

The methodology implemented by authors in [17] was also used in their other papers [10] and [11] on the same material. They focus on complex geometries and different materials. They considered part weight as the response variable but also weight variability. It was found that holding pressure, melt temperature, and injection velocity was statistically significant for part weight, whereas injection velocity alone was significant for weight variation.

In [18], the authors implemented a methodology to optimize two responses in the µIM process of POM parts: shrinkage in the direction parallel to the filling flow and part weight. Five factors were investigated: the injection pressure, the holding pressure, the melt temperature, the mould temperature, and the holding time. The mould and melt temperatures and the holding pressure were significant factors that independently affect shrinkage and part weight. In addition, shrinkage is also affected by a second-order interaction between holding pressure- mould temperature and melt temperature-mould temperature. Finally, optimal conditions for minimizing the total shrinkage and maximizing part weight were determined.

1.2 Flash

As previously described, flash is a typical defect in µIM. In [13], the authors investigated the influence of four process parameters (injection velocity, holding pressure, melt temperature, and mould temperature) on the quality characteristic of polymeric parts. The measured responses were part weight, flow length, and flash area. The results showed that holding pressure and injection velocity was the most influential parameters on part weight, affecting both materials used for the experimentation. Both parameters had a similar effect on flow length, and their effect increased when the feature thickness was below 300 µm. The study showed that the injection speed and holding pressure were the most influential parameters for increasing flash formation for the investigated materials, with consistent effects in both cases. However, this work did not suggest the processing conditions that optimize the process. This work is the first that is considered a flash in the quality assessment of µIM parts. Flash is defined as additional unwanted material typically forming at the edge of the features when material flows between the moulds. Flash is measured as the additional material area on the finished part of their work. However, this choice is impractical from an industrial point of view, as it requires an optical measurement followed by image analysis.

1.3 Conclusions

A literature review comparison is shown in Table 1, along with the present work results discussed later. In the table, the factors varied in the experimentation are indicated with an “X”; the significant ones are marked with “*”. For the significant factors, the direction of the effect is in brackets: the symbol (+) indicated that as the factor level increases, also the response increases; and the symbol (-) suggests that as the factor level increases the response decreases. In the literature, the significance of the factors was assessed using Pareto Charts and a significance level of 5%.

It is difficult to generalize the literature review results because of the different µIM systems, samples, and materials used. However, it appears that holding pressure, melting temperature, and injection speed are the most significant factors affecting the weight of the part.

The present work aims to provide a methodology for optimizing process parameters in µIM. The procedure is based on the definition of a utility function that allows a compromise between two quality features. In this work, the features selected were flash formation and weight, defined through regression equation based on experimental data. It should be noted that this approach can be generalized by using other quality indicators other than the ones used here. The optimization is based on empirical models that cannot be generalized to different materials, µIM systems, and sample geometries. However, the framework is easily replicable.

In the present research, the flash formation was assessed by three experts that provided fast and reliable information about the presence or absence of this defect, making its industrial implementation feasible in opposition to the literature approach.

The process parameters considered in the experimentation were melting temperature, holding pressure, mold temperature, injection speed, and holding time. However, only linear relationships were estimated in the literature due to the type of design of the experiment selected (2^k or 2^k fractional factorials). In the present work, a Central Composite Design CCD was used to assess the influence of the process parameters on the two responses. The advantage of CCD is that it enables the estimation of quadratic effects on the response, rather than just linear relationship.

The paper is organized as follows: In Section 2, the materials and methods used are described; in Section 3, the influence of process parameters on part weight and flash formation. Later, the optimization problem results are presented and discussed.

Table 1. Comparison of the literature on part weight optimization in µIM and result of the present paper (X means that the factor was varied in the experiment, * indicates the significant factors in the analysis).

Paper	**Material**	**Response**	**Mould temperature**	**Melt temperature**	**Injection speed**	**Holding pressure**	**Cooling time**	**Holding time**	**Injection Pressure**
[17]		Part weight	X	X	X	X	X		
	PMMA		*(+)		*(-)	*(+)			
[10]		Part weight	X	X	X	X	X		
	PMMA			*(+)	*(-)	*(+)			
[18]		Part weight	X	X		X		X	X
	POM		*(+)	*(+)		*(+)			
[13]		Part weight	X	X	X	X			
	Polypropylene			*(+)	*(+)				
	ABS			*(+)	*(+)				
[13]		Flash	X	X	X	X			
	Polypropylene		*(+)	*(+)	*(+)	*(+)			
	ABS			*(+)	*(+)	*(+)			
Present work		Part weight	X	X	X	X		X	
	POM			*(+)		*(+)			
Present work		Flash	X	X	X	X		X	
	POM		*(+)	*(+)	*(+)	*(+)			

2. Materials and methods

2.1.Micro-injection moulding system

The material used for experiments is POM (Polyoxymethylene), a polymer used mainly in micro injection moulding due to its flowability that fosters the filling of small cavities. In Table 2, the mechanical and physical properties of POM are reported. POM finds application in micro gears and micro filters for medical industries.

Table 2 – POM main properties

Properties	**Unit**	**Values**
Density	kg/m^3	1400
Tensile modulus	MPa	2700
Yield stress, 50 mm/min	MPa	65
Yield strain, 50 mm/min	%	9.4
Coefficient of linear thermal expansion, longitudinal (23-55)°C	10^{-6}/K	110
Molding shrinkage (parallel)	%	2.10
Molding shrinkage (normal)	%	2.10

The machine used for experimentation is the DESMA Tec Formica Plast 1K which can inject up to 150 mm^3 with a maximum speed of 500 mm/s at 3000 bar and with a clamping force of 10kN, Figure 2 a).

The part identified for the experimentation is a benchmark for micro injection moulding, a double thin plate component with a thickness of 500 µm and an aspect ratio of about 8. The aspect ratio is defined as the ratio between the larger side (3.9 mm) and the smaller side (0.5 mm) of the rectangular section, see Figure 2 b).

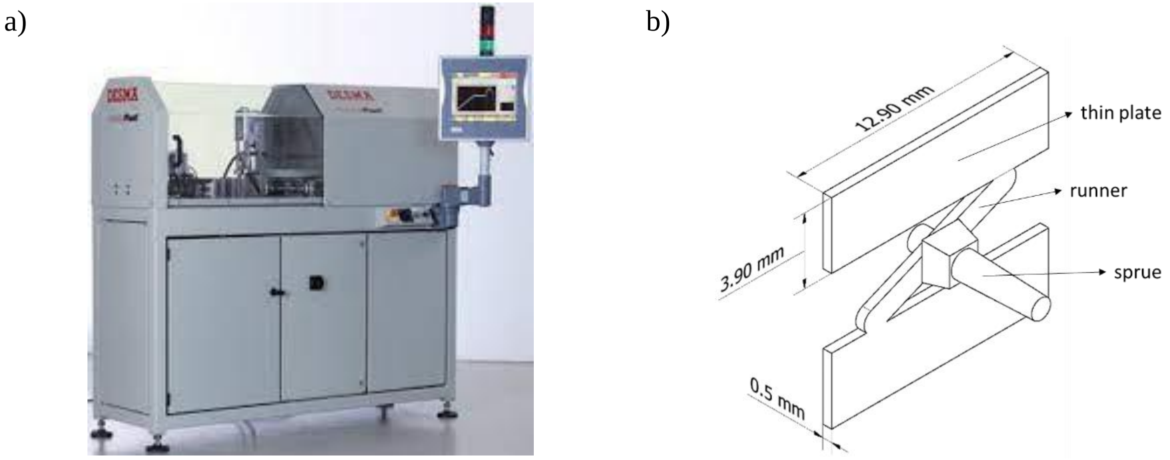


Figure 2 a) DESMA Tec Formica Plast 1K and b) details of the micro moulds and injected part with general dimensions.

The mould was designed considering five ejectors in specific positions, at the beginning and the end of the thin plate and under the sprue. The holes that face the cavity were realized with a tolerance that ensures air evacuation while the polymer fills the cavity but prevents polymer outflow. The lack of burn marks on the moulded parts proves the effectiveness of the proposed solution for air evacuation.

2.2.Design of the experiment

An experimental plan was designed to determine the influence of the process parameters on the weight and the probability of flash formation.

The process parameters varied in the design are mold temperature (T_{mold}), melt temperature (T_{melt}), injection speed (v_{inj}), holding pressure (P_{hold}), and holding time (t_{hold}). The switchover position was set at 12.5 mm (the plunger run was 10.5 mm), and the maximum injection pressure used was 3000 bar, which is also the maximum available on the machine. Based on preliminary experiments, switchover position and injection pressure were considered less influential than the varied process parameters on weight and flash formation.

Parameters were varied according to a CCD that allows the estimation of quadratic effects rather than just the linear effect of the parameters on the responses. This approach is advantageous over the 2^k or fractional 2^k factorial design used in the literature. For this reason, CCD designs are specially used for process optimization [19]. The CCD consists of a full factorial design (2^5 experiments) with the addition of 10 axial points and 20 replicates of the center point. The factorial and axial points were replicated two times, resulting in 104 experiments (2^5+10) x2+20. The distance between the center point and the axial points was set to 1.3 [19]. The order of the experiments was randomized to avoid the effect of systematic errors. For each run, 15 parts were produced. The parts produced in the first five cycles were discharged to stabilize the process, and the remaining ten parts were considered for the analysis. The weight of the parts was measured using a Gibertini sensitive scale with an accuracy of 0.1 mg.

The list of factors levels selected for the experimentation is reported in Table 3. After comparing the suggested range of parameters reported on the material datasheet and state of the art, these levels were identified. The proposed experimentation presents differences compared to the work by Annicchiarico et al.[18]. In [18], the authors focused on the identification of the best injection pressure that maximizes the weight at a defined injection speed; in the present work, a more industrial approach is used by setting the injection pressure to the maximum value and varying the injection speed to identify the best value that maximizes the weight in a range where the probability of flash formation is reduced.

In the first column of Table 3, the coded levels of the variables are reported. All equations were estimated using the coded variables, so the model coefficients are dimensionless, and they measure the effect of changing each design factor over a one-unit variation.

This choice allows a constant injection speed for a large part of the plunger run, avoiding a long acceleration ramp-up.

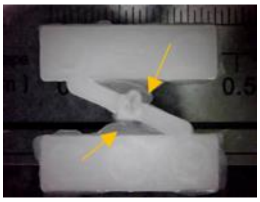
Table 3– Levels of process parameters identified for the experimental campaign

Levels (coded)	**T_{melt} (melt temperature)**	**P_{hold} (holding pressure)**	**T_{mold} (mold temperature)**	**v_{inj} (injection speed)**	**t_{hold} (holding time)**

	[°C]	[bar]	[°C]	[mm/s]	[s]
(+1.3)	236	1650	106	157.5	3.3
(+1)	230	1500	100	150	3
(0)	210	1000	80	125	2
(-1)	190	500	60	100	1
(-1.3)	184	350	54	92.5	0.7

In this work, flash formation is described as a categorical variable. It was evaluated independently by three micro injection moulding experts based on direct observation of the part with a magnifying glass. The voting categories were 0 = no flash, 1 = flash. In case of doubtful evaluation, the part was assigned the vote agreed by two out of three experts. An example of an evaluation of flash is reported in Table 4.

Table 4. Experts' evaluation of Flash in two different samples. Arrows indicate the presence of Flash.

Run Order		**Categorical variable**		
		0= no flash 1= flash		
		Expert 1	Expert 2	Expert 3
2		0	0	0
6		1	1	1

2.3.Methodology for the selection of the optimal conditions

Based on the results of the CCD design, two regression models were estimated to predict part weight and the probability of flash formation based on the process parameters considered. In the notation, **x** is the vector of the parameters defined as **x** = (T_{melt}, p_{hold}, T_{mold}, v_{inj}, t_{hold}).

Flash is a binary response variable, so a binary logistic regression was estimated. The logistic model describes the probability of flash formation, P_{FLASH}, as a function of the process parameters. The logistic model is:

$$P_{FLASH} = \frac{e^{\hat{y}}}{1+e^{\hat{y}}} \text{ where } \hat{y} = \hat{y}(\mathbf{x}, \hat{\boldsymbol{\gamma}}) \tag{1}$$

Variable y is the result of the experts' evaluation on flash, so y ∈ {0;1}. P_{FLASH} is, instead, the probability of flash formation given the vector **x** and $\hat{\gamma}$, which are the estimated coefficients of the logistic equation; so, $P_{FLASH} \in [0,1]$. This approach is a simplification because it does not consider the severity of flash, requiring more than two response levels. However, the proposed procedure can be easily generalized using an ordinal logistic regression model when more than one severity level of flash is of interest.

Weight is a continuous response variable, and a linear regression model was used:

$$\hat{w} = \hat{w}\left(\mathbf{x}, \hat{\boldsymbol{\beta}}\right) \tag{2}$$

In Eq (2), $\hat{\boldsymbol{\beta}}$ are the estimated coefficients of the least square regression model.

Only significant terms are included in Eq (1) and Eq (2) to improve the predictive quality. These equations are reported in coded units (i.e., using the first column of Table 3) so that the magnitudes of the coefficients are directly comparable.

The experimentation started by assessing the presence of flash on the parts and estimating the probability of flash formation using logistic regression. Then, if the part was defective (i.e., flash is present), it was not considered for the weight assessment and the following estimation of the regression equation. So, the model in Eq (1) is obtained using 104 data points; while Eq (2) uses 71 data.

In conclusion, the objective of the analysis is to determine the optimal processing condition considering both the weight of the part and the probability of flash formation. The problem is solved through the utility function:

$$u(\mathbf{x}, \hat{\boldsymbol{\beta}}, \hat{\boldsymbol{\gamma}}) = \hat{w}\left(\mathbf{x}, \hat{\boldsymbol{\beta}},\right) \times \left[1 - P_{FLASH}\left(\mathbf{x}, \hat{\boldsymbol{\gamma}}\right)\right] \qquad \mathbf{-1} \le \mathbf{x} \le \mathbf{1} \tag{3}$$

The function in Eq (3) was maximized to find the optimal set of parameters, **x**. When P_{FLASH} is close to 0, the utility function maximizes the weight of the part, which is a proxy of a successful filling. The weight is "penalized" in the processing conditions with a non-zero probability of flash formation, the weight is "penalized," and the utility is reduced. Therefore, the region where the flash formation is expected results in a lower utility.

The optimization was carried out in the range [-1;1] even though the parameters varied [-1.3; 1.3]. This choice was made because, in the limited range [-1;1], the variance of the predicted response is minimized [19], allowing a robust selection of the optimal conditions.

The workflow of the experimental analysis for selecting the optimal process parameters in micro-injection moulding is illustrated in Figure 3.

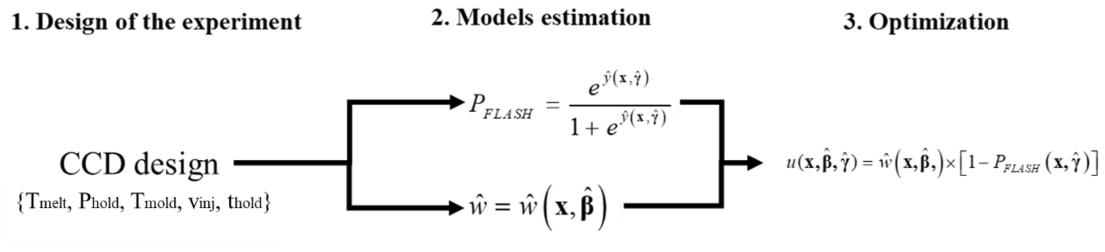


Figure 3. Workflow of the experimental analysis

3. Results and discussion

In this section, the experimental results are described and discussed. Firstly, the effect of the parameters on the probability of flash formation and weight are reported. The estimated regression equation defines the utility function and selects the optimal processing condition.

3.1. Influence of process parameters on flash and weight

The significant factors affecting the probability of flash formation are shown in Table 5.

Table 5. Logistic regression model on the flash formation

Source	DF	Chi-Square	p-value (Wald test)
Regression	5	23.82	0.000
T_{melt}	1	6.27	0.012
P_{hold}	1	14.8	0.000
T_{mold}	1	15.44	0.000
v_{inj}	1	19.63	0.000
$v_{inj}*P_{hold}$	1	12.19	0.000

Four process parameters are significant: melting temperature, holding pressure, mold temperature, and injection speed. Holding time is not significant. The interaction between the injection speed and holding pressure is also highly significant. The estimated logistic equation in coded variables is the following:

$$P_{FLASH} = \frac{e^{\hat{y}}}{1+e^{\hat{y}}} \tag{4}$$

where $\hat{y} = -3.401 + 1.257\,T_{melt} + 3.85\,P_{hold} + 2.285\,T_{mold} + 4.95\,v_{inj} - 3.482\,P_{hold}v_{inj}$

A positive coefficient indicates that the probability of flash formation increases as the value of the predictor increases. The flash probability increases when mold temperature, melt temperature, injection speed, and holding pressure move towards their highest value. These four factors influence the viscosity of the material.

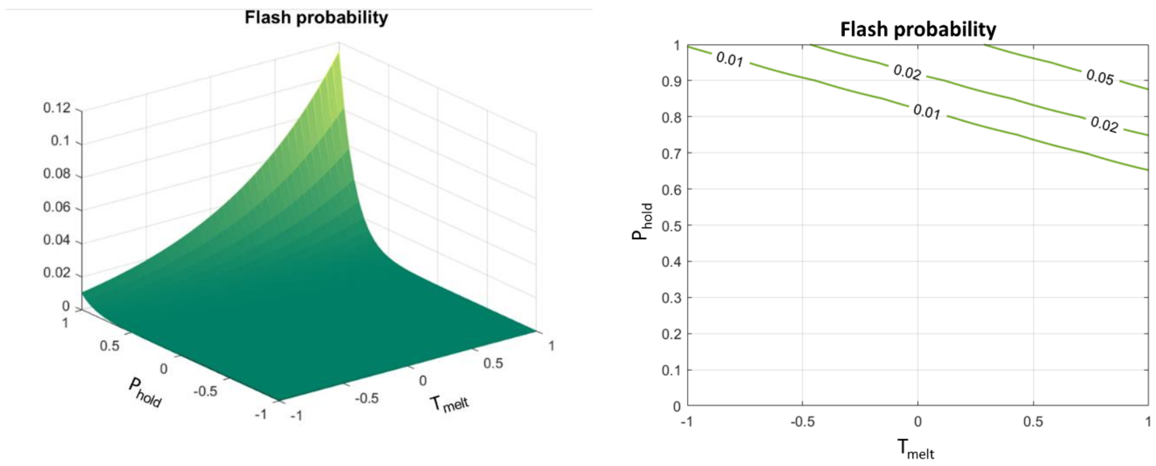
When the viscosity decreases, the polymer flows better in the channels—the viscosity decreases at high melt temperature and high injection speed [6, 7]. The combination of high injection speed and high holding pressure can cause the overcoming of the clamping force with the risk of flash formation.

Conversely, the flash probability is reduced by the interaction between injection speed and holding pressure. The sign of the interaction coefficient suggests an adjustment of P_{hold} and v_{inj} that can reduce the probability of flash formation. This probability is reduced when these parameters are cross-balanced. The polymer's decreasing viscosity due to the high injection speed [6, 7] is compensated by the reduced holding pressure, ensuring that the material does not overcome the clamping force. When the viscosity is higher, an increase in the holding pressure guarantees the correct formation of the part.

In Figure 4, the surfaces and contour plots of Eq (4). In Figure (a), P_{hold} and T_{melt} are considered, while v_{inj} and T_{mold} are set equal to -1; in Figure (b), v_{inj} and T_{mold} are varied, while P_{hold} and T_{melt} are set to -1; in Figure (c) the effect of P_{hold} and v_{inj} are shown, while T_{mold} and T_{melt} are set to -1. Contour plots in Figure 4 a) and b) are plotted considering P_{hold} and v_{inj} in the range [0, 1] rather than [-1, 1] for clarity purposes.

The surfaces show that the probability of Flash formation is maximum when all variables are set to their highest value. Also, in a large region of the parameters, the probability of flash formation is equal to 0.

a)



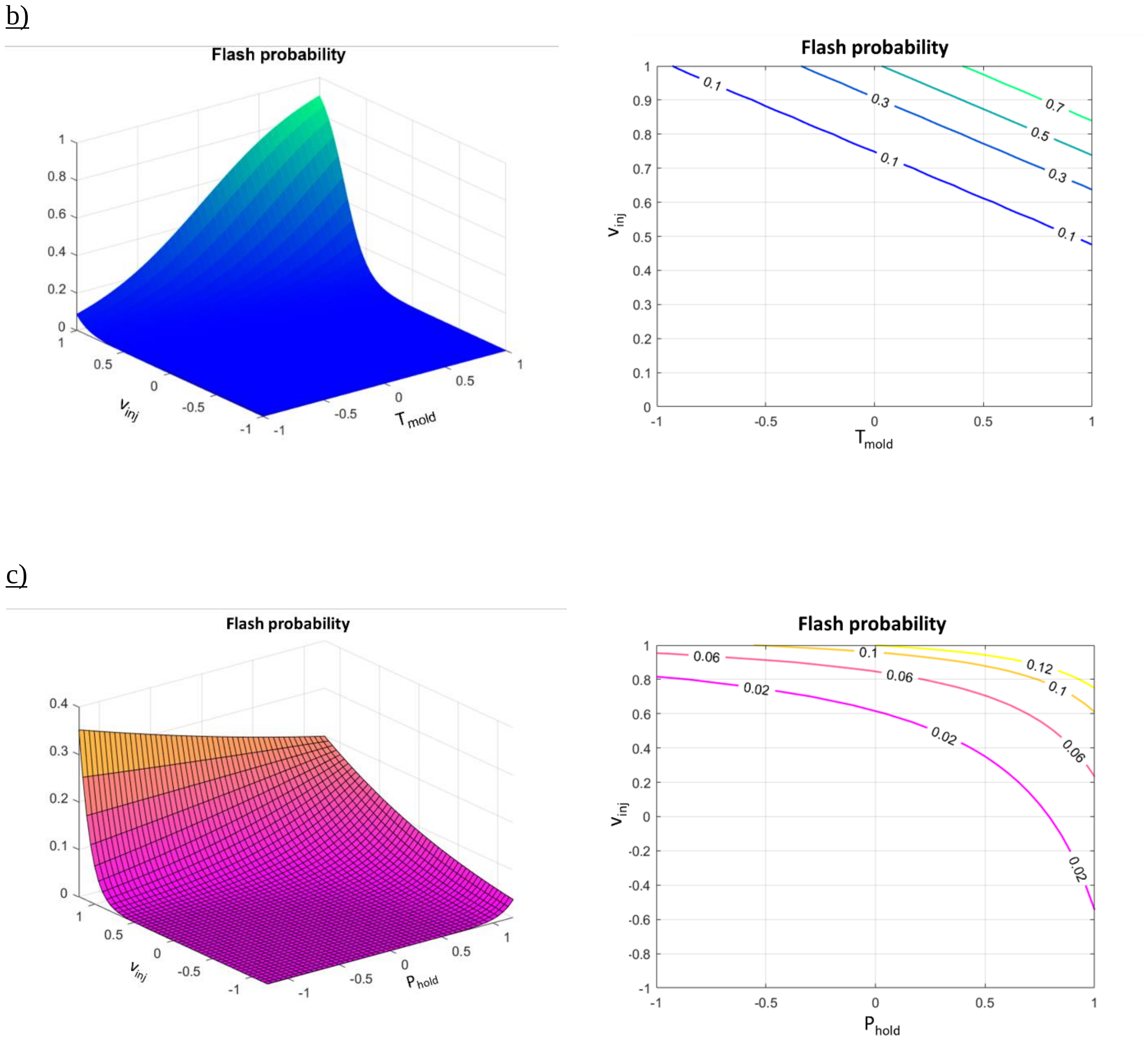


Figure 4. Surfaces and contour plots of Flash probability in Eq (4). a) as a function of T_{melt} and P_{hold} when T_{mold}=v_{inj}=-1. b) as a function of T_{mold} and v_{inj}, when T_{melt} = P_{hold} =-1. c) as a function of P_{hold} and v_{inj} when T_{mold}=T_{melt}=-1

The weight function was estimated using only the conditions that resulted in a lack of flash, 70 data points. The result of the statistical analysis on part weight is reported in Table 6; only significant factors were reported in Table. The p-values show that the significant factor for weight is T_{melt} and P_{hold}, while v_{inj}, T_{mold}, and t_{hold} were not significant. The estimated regression equation in coded variables is shown in Eq(5), and the adj-R^2 of the model is 95.75%.

Table 6. ANOVA table for the influence of process parameters on part weight

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**p-value**
Model	4	3381.26	845.32	525.1	0.000
T_{melt}	1	68.41	68.41	42.49	0.000
P_{hold}	1	2896.2	2896.2	1799.08	0.000

$P_{hold}*P_{hold}$	1	376.13	376.13	233.64	0.000
$T_{melt}*P_{hold}$	1	113.43	113.43	70.46	0.000
Error	65	143.27	1.61		
Total	69	3524.53			

$$\hat{w} = 88.114 + 1.091 T_{melt} + 5.693 P_{hold} + 2.193 P_{hold}^2 + 0.884 T_{melt} P_{hold} \quad (5)$$

The weight surface is represented in Figure 5.

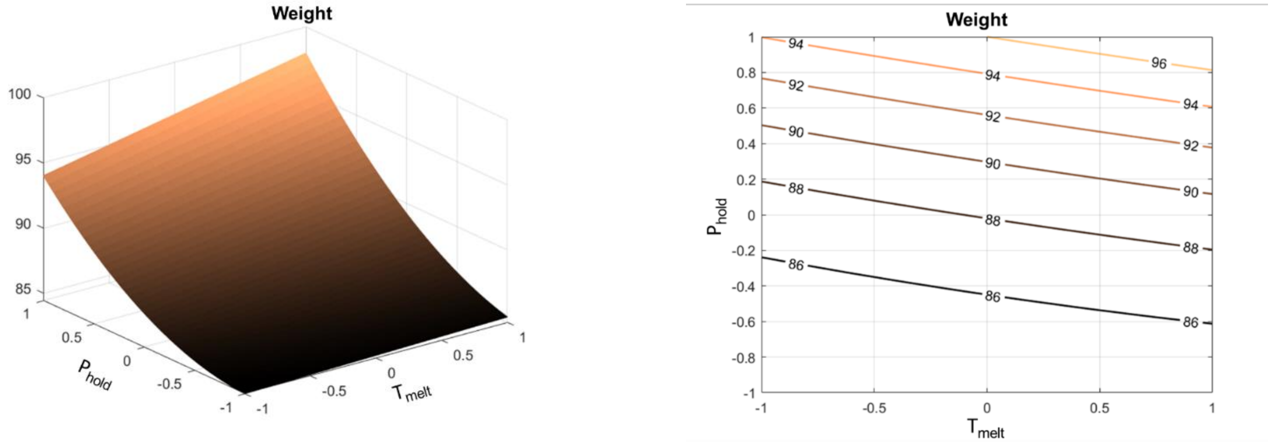


Figure 5. Surface and contour plot of Part weight in Eq (5) function of T_{melt} and P_{hold}.

All coefficients are positive, showing that the weight increases as T_{melt} and P_{hold} increase.

The influence of holding pressure was expected since its increase allows for more material to fill the mould cavity and compensate for shrinkage before complete freezing. Also, melting temperature influences part weight; high melt temperature facilitates mould filling due to the improved polymer flow inside the cavity. The weight of the part is maximized when both P_{hold} and T_{melt} are at the highest level, which is also the region where the probability of flash formation is maximized. Therefore, a non-constrained optimization problem would lead to a non-feasible region resulting in a high defect rate.

It is worth noting that the use of the CCD design allowed to estimate the quadratic effect of holding pressure on part weight which was not reported in the literature before.

3.2.Optimization

The utility function in Eq (3) identifies the optimal processing conditions of the combinations of P_{hold}, T_{melt}, T_{mold}, and v_{inj} that maximize the weight. The utility in Figure 6 is plotted against P_{hold} and T_{melt} while T_{mold}=v_{inj}=-1. Utility increases as P_{hold} and T_{melt} increase; however, the utility sees a sharp decrease as these two variables approach their maximum value. The reduction in the utility is due to the increased probability of flash formation, as shown in Figure 4.

The maximum utility (93.54) is achieved at T_{melt}=1, P_{hold}=0.7, and T_{mold}=v_{inj}=-1, as reported in Table 7.

Optimal processing conditions Coded variables					**Optimal processing conditions Uncoded variables**					**Weight (mg)**	**Flash probability**
T_{melt}	P_{hold}	T_{mold}	v_{inj}	t_{hold}	T_{melt} (°C)	P_{hold} (bar)	T_{mold} (°C)	v_{inj} (mm/s)	t_{hold} (s)		
1	0.7	-1	-1	-1	230	1350	60	100	1	94.9	1.4%

Table 7. Optimal process parameters based on the maximization of the utility function

T_{mold} and v_{inj} should be set at their lowest level because, in this condition, the probability of flash formation is minimized (see Figure 4 a), b)), and they do not influence the weight of the part. On the contrary, T_{melt} should always be set at the highest level because it maximizes the weight of the part. Hold time t_{hold} does not affect the weight nor the flash probability, so it is set at the values that maximize the productivity of the process; that is, t_{hold} = 1 s. As previously noted, the minimization of the probability and the weight maximization are opposite objectives in terms of process parameters selection: P_{hold} and T_{melt} should be maximized to maximize weight. However, at the same time, this choice leads to the maximization of the flash formation probability.

The optimization results suggest correctly using a medium/high level of holding pressure and a high melt temperature to favor the reduction of viscosity [7]; this combination allows to correctly fill the cavity and complete the component by maximizing the part weight and minimizing the risk of flash formation. The injection speed is set at its lower value, ensuring the air's displacement from the mould through the vent slots. The optimal mould temperature is low, facilitating heat dissipation and avoiding polymer degradation due to heat concentration. The utility function finds a compromise between part weight and the probability of flash formation; for this reason, in the optimal condition, there is a small but non-zero probability of flash formation, equal to 1.4%. Based on how the utility function is defined, the optimal process condition in Table 7 is the best compromise.

A vast region of parameters ranging from Tmelt [-1;1] and Phold [0.5; 1] shares similar utility values with the optimal values. Red contour lines in Figure 7 indicate this region.

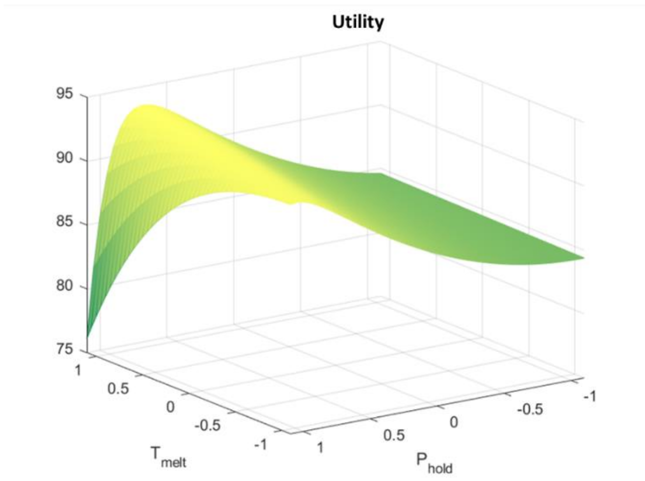


Figure 6. Utility as a function of P_{hold} and t_{melt} ($v_{inj}=t_{mold}=-1$)

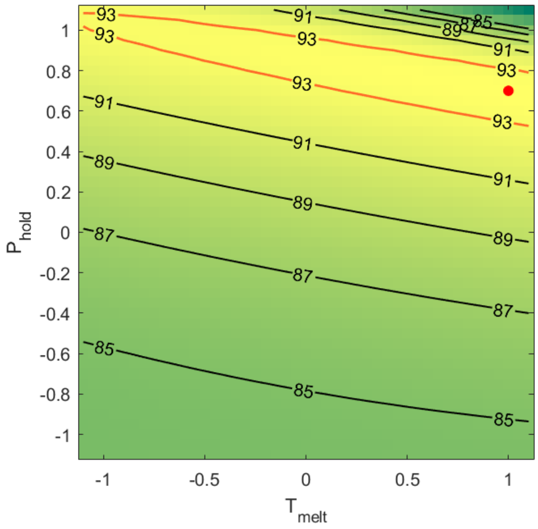


Figure 7. Contour plot of the utility function. The red dot indicates the optimal processing condition.

In conclusion, optimizing processing conditions in µIM requires a compromise between maximizing weight and minimizing the likelihood of producing components with flash. The optimal point involves a reduction of the holding pressure, which results in lower pressure on the mold cavity with a consequent decrease in the risk of reaching the limit of the clamping force. Therefore, a high temperature of the molten polymer must be used to reduce viscosity to correctly fill the microcavity and, at the same time, to compensate for the pressure reduction. This result is coherent with the industrial practice and validates the presented methodology.

4. Conclusions

The quality in the µIM process can be defined by several features that need to be optimized at the same time. In this work, the quality of the molded parts was assessed based of the presence of flash and the weight.

An extensive experimental campaign based on a Central Composite Design was carried out to investigate the influence of five process parameters (holding pressure, molding temperature, injection speed, holding time, and melting temperature) on the quality of the final parts.

Contrary to the literature, flash formation is evaluated by three injection molding experts that provide a binary response to determine if flash is formed, 1= flash and 0=no flash. This approach is replicable in an industrial environment where defects should be assessed instantly. However, it has limitations because different levels of severity of flash cannot be determined. Nevertheless, the methodology proposed is not affected by this simplification as one could use a categorical regression equation to consider more than two levels of flash.

The experimental data were used to estimate two regression models: a linear model describing the weight of the component and a logistic model for the probability of flash formation. The experiment results show that four process parameters are significant for flash formation (melting temperature, holding pressure, mould temperature, and injection speed). However, part weight is affected only by melting temperature and holding pressure. Holding time did not affect the part weight or flash formation. The selection of the optimal level of the process parameters was carried out using a utility function. The utility function aims at finding a compromise between the maximization of the weight and the minimization of the probability of flash formation. According to the optimization results, a medium/high holding pressure level should be combined with a high melting temperature. This combination results in a lower viscosity of the POM material and a better mold filling. Injection speed and moulding temperature should be set at their lowest level; a low injection speed prevents air from being trapped in the cavity, which could cause burn marks, while a low moulding temperature improves heat dissipation during the process.

It is worth noting that thanks to the experimental design used, it was possible to identify the parameters' quadratic effect, which was not possible in the previous literature due to the use of fractional factorial design.

Suggestion for future research is the set up a procedure that can solve a non-deterministic optimization problem that considers the sampling variability of the estimated regression equations, resulting in a confidence region of the optimal solution.

Supplementary data

All the experimental data used in this article are provided as supplementary material.

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