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Investigation of the influence of vacuum venting on mould surface temperature in micro injection moulding

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Abstract The application of vacuum venting for the removal of air from mould cavity has been introduced in injection moulding with the intent to enhance micro/nano features replication and definition. The technique is adopted to remove air pockets trapped in the micro-features, which are out of reach for conventional venting technologies and can create considerable resistance to the melt filling flow. Nonetheless, several studies have revealed a negative effect on replication that could possibly arise from the application of vacuum venting. Although the incomplete filling of micro-scale features has often been attributed to poor venting, the limited research examining the application of vacuum venting has produced mixed results. In this work, the effect of air evacuation was experimentally investigated, monitoring mould and polymer temperature evolution during the micro injection moulding process by means of a high speed infrared camera and a sapphire window, which forms part of the mould wall. The results show that air evacuation removes a mould surface heating effect caused by rapid compression of the air ahead of the flow front and subsequent conduction of that heat into the mould surface. Hence, with the increase of the surface-to-volume ratio in micro-cavities, air evacuation has a detrimental effect on the cavity filling with polymers that are sensitive to changes of the mould temperature.

Keywords Micro injection moulding · Condition monitoring · Cavity air evacuation · Mould temperature

1 Introduction

Micro injection moulding (μIM) is a reliable and cost effective means of producing a wide range of micro components in thermoplastics. When replicating micro features, surface quality is one of the most important process characteristic and it constitutes a manufacturing constraint in applying this technology to a wider range of micro-engineering applications.

Consequently, the study of factors that affect the replication capabilities is very important in order to gain insight of the process and overcome technological limitations that still persists. In the last decade, many research groups have focused their attention on the factors that affect the replication quality during the μIM process, in particular on process conditions and cavity geometry [1]. The results reported in the literature indicate that among the main factors, mould temperature (T_m) markedly affect the replication degree of micro features. According to Ong et al. [2], mould temperature not only determines the replication capability of the process, but also its efficiency and part quality. In fact, a high value of T_m counteracts the short freezing time and thus extends the flow length of polymer melts when filling micro features.

In micro injection moulding the polymer flow is characterised by a high surface-to-volume ratio, which leads to a high cooling rate of the polymer melt in the mould cavity. The polymer melt near the wall of the cavity cools to form a solid skin and reduces the cavity cross section. Thus, premature material freezing precludes the complete filling of micro features, not allowing the achievement of the required replication accuracy [7]. Moreover, the pressure generated by the air not evacuated from the cavity can increase the resistance to the flow, causing an incomplete replication. Two solu-

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Table 1: Evaluation of cavity air evacuation efficiency for micro-injection moulding, results from different research groups.

Feature size **Width (μm)**	 **Aspect Ratio**	**Injected Material**	**ΔDR %**	**Ref.**
100	1	ABS	> 0	C.A. Griffiths, at al., 2010 [3]
2÷20	12	PMMA,PP,HDPE	/	Liou and R.-H. Chen, 2006 [4]
8	0.5	PMMA	< 1	Huang-Ya and Wen-Bin, 2009 [5]
60	4	PP	/	Zhen and Zhang, 2009 [6]
80	10	POM	$4.6 \div 5.4$	Ong et al., 2006 [2]

tions have been identified to improve the process. First, the mould temperature needs to be set higher than the transition temperature of the polymer (T_g) to reduce its viscosity during the filling stage [8]; secondly, vacuum venting can be applied to avoid possible air traps [9]. This research work is focused on the influence of the cavity air evacuation on the flow front temperature during the μIM process.

The application of vacuum venting for the evacuation of air from the cavity has been introduced in injection moulding with the intent to further enhance feature replication and accuracy (sharpness of edges) by removing air pockets trapped in the micro features, which can resist the melt filling flow [10]. At the macro scale, air entrapment inside the moulds is usually avoided by evacuating the air through vents, that are machined on the interior surfaces of the mould plates, in the parting plane, and the air is expelled as the melt fills up the mould. Alternatively, the clearance gaps around the ejector pins are sufficient to vent the mould. In micro injection moulding the venting of the mould prior to injection is a critical task beacuse of the high values of injection speed [11].

According to Menges et al. passive venting should be adopted for micro injection moulding applications [12]. This type of venting is used when micro structures are present, since conventional venting gaps are too large compared to the dimensions of the cavities. Thus, the cavity is evacuated by means of an evacuation system [13] and the resistance from compressed air in micro cavities is reduced [14]. Additionally, the evacuation of air from the cavity can prevent the gasification of the polymer which is due to the residual gases that are present in the cavity at the beginning of the filling phase [4].

However, Sha et al. observed a negative influence of vacuum venting on micro features replication [15]. They speculate that, air evacuation could lead to a decrease of the surface temperature in micro features as a result of removing warm air from the cavity. Hence, with the increase of the surface-to-volume ratio in micro cavities, air evacuation could have a detrimental effect on the melt fill, especially for polymers that have a high temperature dependence of viscosity [16].

The research works examining the application of vacuum venting have produced conflicting results, as summarized in Table 1, where ΔDR indicate the increment in percentage of the degree of replication applying cavity air evacuation.

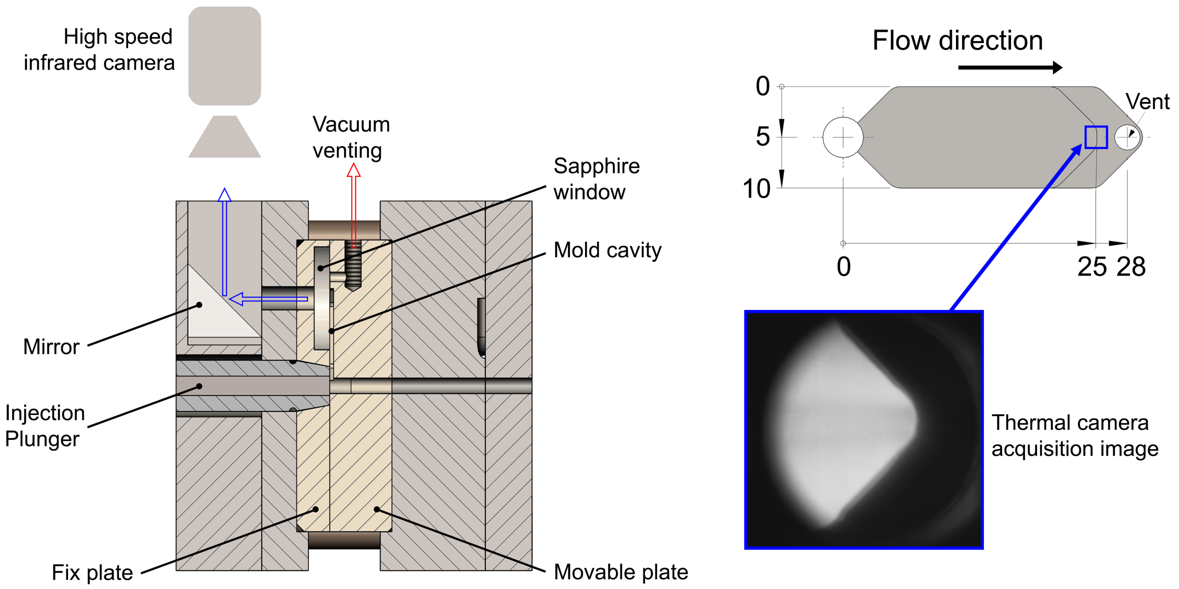
While the beneficial effect of applying a vacuum venting in μIM has been proven to derive from the removal of air trapped inside the narrow cavities, which obstacolate the polymer flow [4], [10], the supposed negative effect of this auxiliary technology on the mould temperature [15] has not been experimentally demonstrated. The aim of this work is the direct measurement of the effect of cavity air evacuation on the mould/polymer temperature, using a novel experimental setup.

The experimental section describes the mould design, the material selection and characterization and the infrared acquisition setup for temperature measurement. Section 3 discusses the experimental results, focusing the attention on the effect of vacuum venting on mould surface temperature during the μIM process. Moreover, the main effect of process parameters and their interactions are analyzed. Concluding, section 4 reports how in μIM the effect of vacuum venting has to be carefully considered as it decreases significantly the mould temperature, which plays a fundamental role in the process.

2 Experimental Setup

2.1 Part and Mould Design

The tool used to perform the experiments was based on the Hasco K-standard modular system. However, the standard system was modified to integrate a sapphire window and a mirror for the mould/melt temperature monitoring. As shown in Fig. 1(a), a pocket was machined on the fixed plate of the mould to accommodate



(a) (b)

Fig. 1: Mould design (a); schematic top view of the part design and the image from the IR camera (b)

a 45° tilted first surface gold mirror, which was aligned with the sapphire window overlooking the mould cavity.

The test part design used in this study was characterised by overall dimensions of 10 mm x 25 mm x 1 mm thickness Fig. 1(b). The part geometry was designed considering the aim of the analysis. In particular: (i) the length (25 mm)was chosen in order to ensure a sufficient filling time for the thermal camera acquisition signal; (ii) the width (10 mm) was chosen according to the sapphire window dimensions and (iii) the thickness was calculated considering the maximum shot size of the μIM machine. Moreover, the tapered shape of the cavity was designed in order to emphasize the effect of the cavity air evacuation from the mould. The cavity was vented by means of an evacuation system. A channel was machined on the moving plate of the mould to host an O-ring, which surrounds the cavity and seals the mould-parting plane. A vacuum pump was connected to the mould with a vent that was machined on the opposite side of the gate and placed inside the sealed area. The channel for the evacuation of the air from the cavity has a thickness of 50 μm and it covers all the width of the mould cavity. The vacuum pumping system had a rated pumping speed of 0.95 mm^3/s and capacity of 0.5 mm^3. The evacuation of air from the cavity obtained with the vacuum pump allowed the achievement of pressure inside the cavity lower than 6 mbar before the injection. The evacuation of the air from the cavity was applied for 10 s before the injection and for all its time, as suggested by Yokoi et al. [17].

Table 2: Test material properties

Material	Topas 5013 L-10
Category	COC
Structure	Amorphous
MFI (200 °C - 5kg)	47.05 [g/10min]
T_g	134 °C

The heating stage was realised using 4 electrical resistive heaters: 2 in the fixed plate and 2 in the movable one.

2.2 Test Material

A commercial cyclic olefin copolymer (TOPAS, COC 5013 L-10) was used for the experimental work. Topas COC resins are suitable for the production of transparent mouldings for use in optical data storage, optics (e.g. lenses, sensors) and industrial products. Due to their high flowability, low density, high transparency and low birefringence, these materials are designed to use in micro injection moulding [16]. Its properties are provided in Table 2.

For the μIM tests, a state-of-the-art micro injection moulding machine (Wittmann Battenfeld, MicroPower 15) with a maximum clamping force of 150 kN and a maximum injection speed of 800 mm/s was used. The plasticising screw has a diameter of 14 mm and the injection plunger has a diameter of 5 mm.

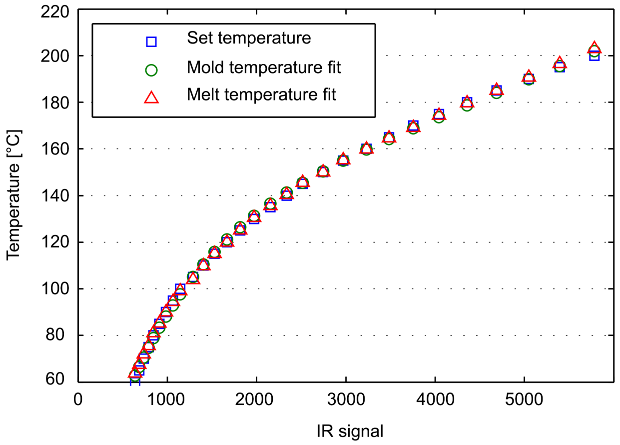


Fig. 2: IR camera calibration for mould (○) and melt (△) temperature

2.3 Condition Monitoring

In this study the effects of the cavity air evacuation on the melt flow front temperature was investigated using a high-speed, high sensitivity infrared camera (Ircam Equus 81k SM). The camera has a cooled indium antimonide (InSb) detector with the spectral range of 1.5 to 5.0 μm. It can capture 386 frames per second at the full frame size of 320 x 256 pixels, and can achieve 30 000 frames per second in a windowing mode. This very fast IR camera was used to measure the flow temperature of the polymer inside the mould cavity during the μIM process.

The IR camera was calibrated before the injection moulding experiments for both the mould and the polymer temperature. In the first case, the mould temperature was set using the control system integrated on the injection moulding machine and after a thermal stabilisation of 300 s, an IR signal was recorded. A similar procedure was used for the calibration with the polymer. In this case, the polymer was injected inside the mould cavity where it was left for 300 s to thermally stabilise before acquiring the IR signal. The calibration temperature ranged from 60 °C to 200 °C with increments of 5 °C and each acquisition was repeated three times. The experimental data were fitted with a general exponential model (Eq. 1):

$$f(x) = a\cdot \exp(b\cdot x) + c\cdot \exp(d\cdot x) \qquad (1)$$

The coefficients of Eq. 1 and the parameters regarding the goodness of fit are reported in Table 3. In particular, the goodness of fit is related to the R-square value, equal to 0.9997, which means that the fit explains 99.97% of the total variation in the data about the average. As shown in Figure 2, there are no significant differences between the two considered models. For this reason, the mould temperature fitted model was chosen for the entire work.

2.4 Experimental Design

A design of experiments (DoE) approach was applied to design and analyse the experimental campaign. A two-level, three-factor, full factorial plan was used. For each run, the data collected on the first 10 cycles were discarded in order to stabilise the process. Each treatment of the DoE was repeated three times in a completely randomised order for 24 runs, with the aim of minimising the interference of external variability sources [18]. Factors investigated were the mould temperature (T_{m}), the injection velocity (V_{inj}) and the presence of air evacuation (E_{a}). The choices of the upper and lower levels for the factors were derived from a literature review, recommendations of the material supplier and the technological limits of the available experimental setup. The range values for each factor are summarised in Table 4.

Table 3: Coefficients of the fitted general exponential model and goodness of fit parameters

General exponential model

$f(x) = a\cdot \exp(b\cdot x) + c\cdot \exp(d\cdot x)$

Coefficients (with 95% confidence bounds)			
For mould temp.		**For melt temp.**	
a	126.1	a	131.8
b	8.16E-05	b	6.877E-05
c	-139.5	c	-120.1
d	-0.00107	d	-0.00098
Goodness of fit			
For mould temp.		**For melt temp.**	
SSE	47.7300	SSE	6.738
R-square	0.9991	R-square	0.9997
Adjusted R-sq.	0.9989	Adjusted R-sq.	0.9997
RMSE	1.3820	RMSE	0.5955

Table 4: Factors and levels for the design of the factorial plan

Level	**Tm** [°C]	**V$_{\mathrm{inj}}$** **[mm/s]**	**Ea**
(+1)	140	850	On
(-1)	80	350	Off

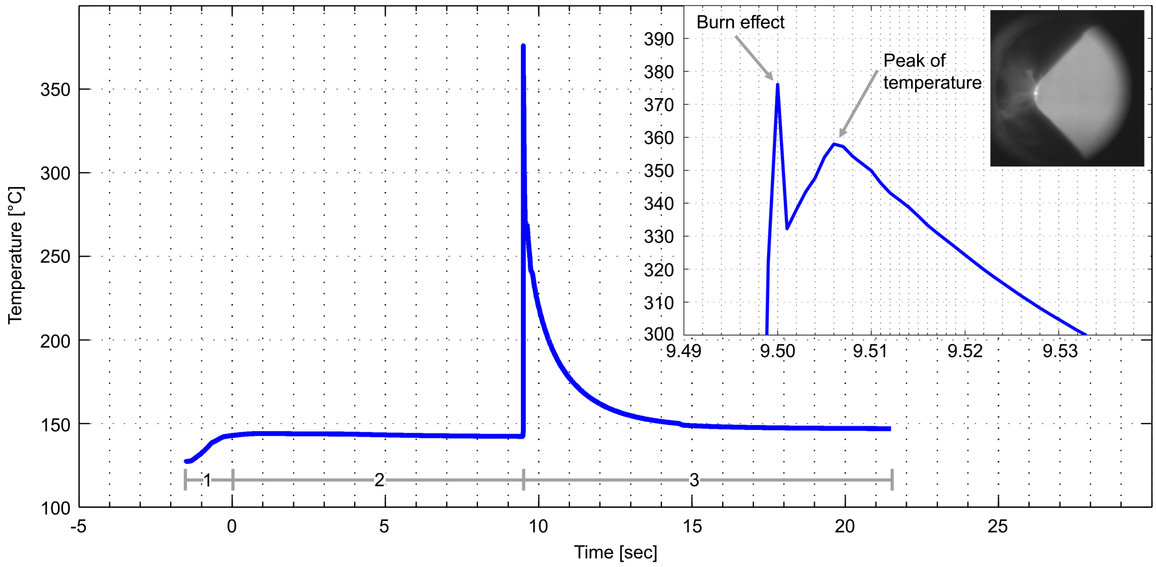


Fig. 3: Temperature profile: (1) Mould closure; (2) Injection delay; (3) Filling and packing stage. On the upper right corner, the magnification of the temperature profile in the injection zone.

The parameters that were not considered as design factors were fixed at levels suggested from literature:

- Barrel temperature: 240 - 280 - 300 - 320 °C;
- Shot size: 220 mm^3;
- Holding pressure: 40 MPa for 9 s;

The cavity pressure before the injection was set at 3 mbar. The vacuum venting was applied for 10 s before the injection and for all its duration. The response variable for this analysis was chosen to be the peak of temperature of the flow front inside the mould cavity ($\bar{T}_{peak}$). As shown in Fig. 3, the higher peak of temperature is related to the burn effect caused by the rapid compression of the air ahead of the flow front, while the second peak of temperature is related to the maximum flow front temperature. For each test, the signal acquired with the IR camera, was elaborated using the software Works from Ircam. The signal was extracted from a region of interest (ROI) of the size of 70 x 50 pixels as shown in Fig. 4 and it has been applied the general exponential model (Eq. 1) in order to obtain the temperature profile.

3 Results and Discussions

The factorial design was analysed in order to comprehend which factors and interactions are statistically significant for the variation of the flow front temperature inside the mould cavity.

Table 5 presents the results obtained from the experiments. For each level of the experimental design, the average peak temperature ($\bar{T}_{peak}$) and the standard deviation are reported. A general linear model was used to perform an univariate analysis of variance, in-

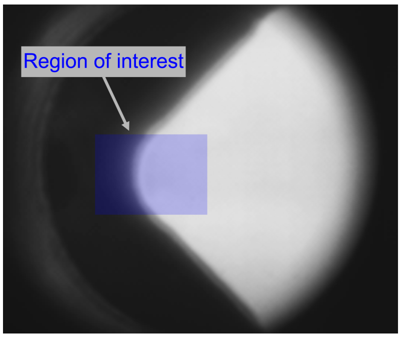
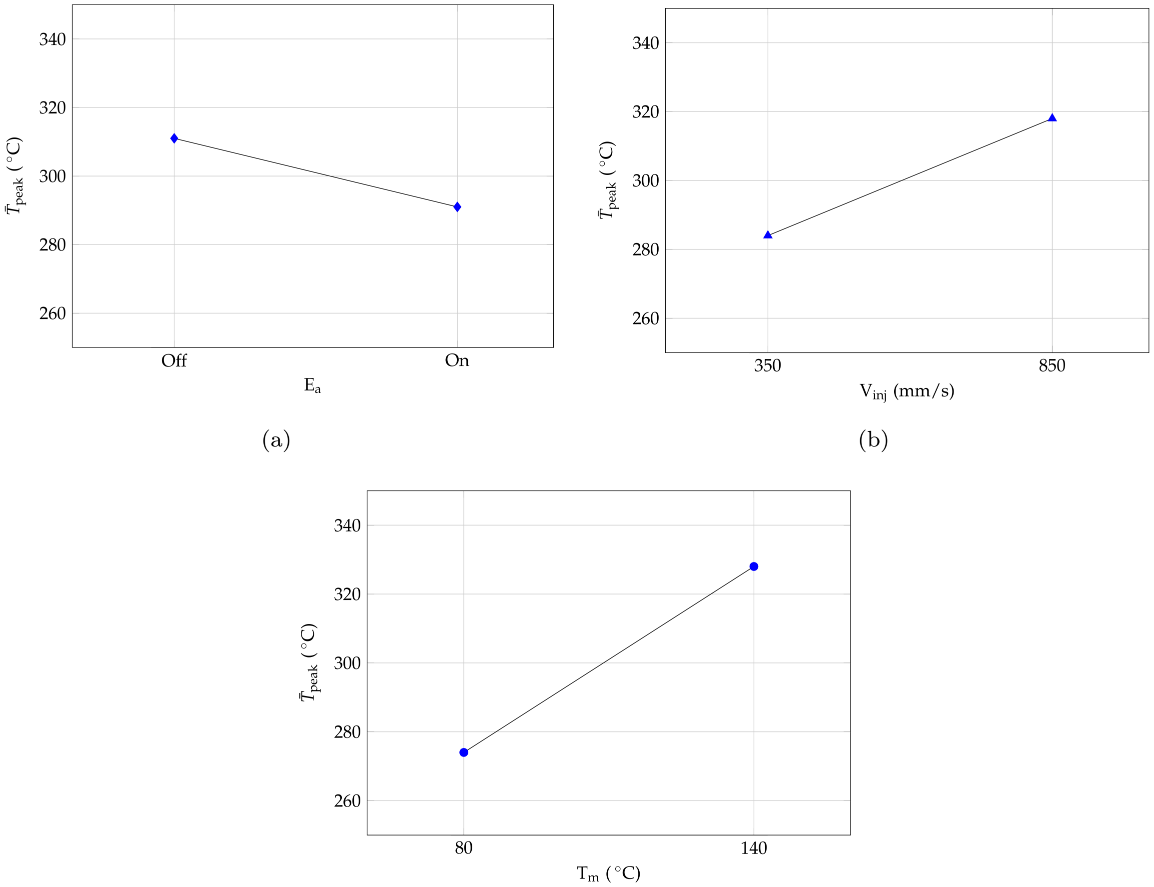


Fig. 4: Thermal camera acquisition image and the region of interest (ROI)

Table 5: Results of the experimental campaign

Tm [°C]	$\mathbf{V_{inj}}$ **[mm/s]**	**Ea**	$\bar{T}_{\mathbf{peak}}$ [°C]	**Std. dev** [°C]
80	350	Off	269.0	2.84
140	350	Off	309.7	2.34
80	850	Off	293.7	3.00
140	850	Off	370.2	2.48
80	350	On	260.9	2.61
140	350	On	297.6	2.14
80	850	On	274.2	2.58
140	850	On	331.6	3.12



(a) (b)

(c)

Fig. 5: Main effect plots of (a) air evacuation, (b) injection speed and (c) mould temperature.

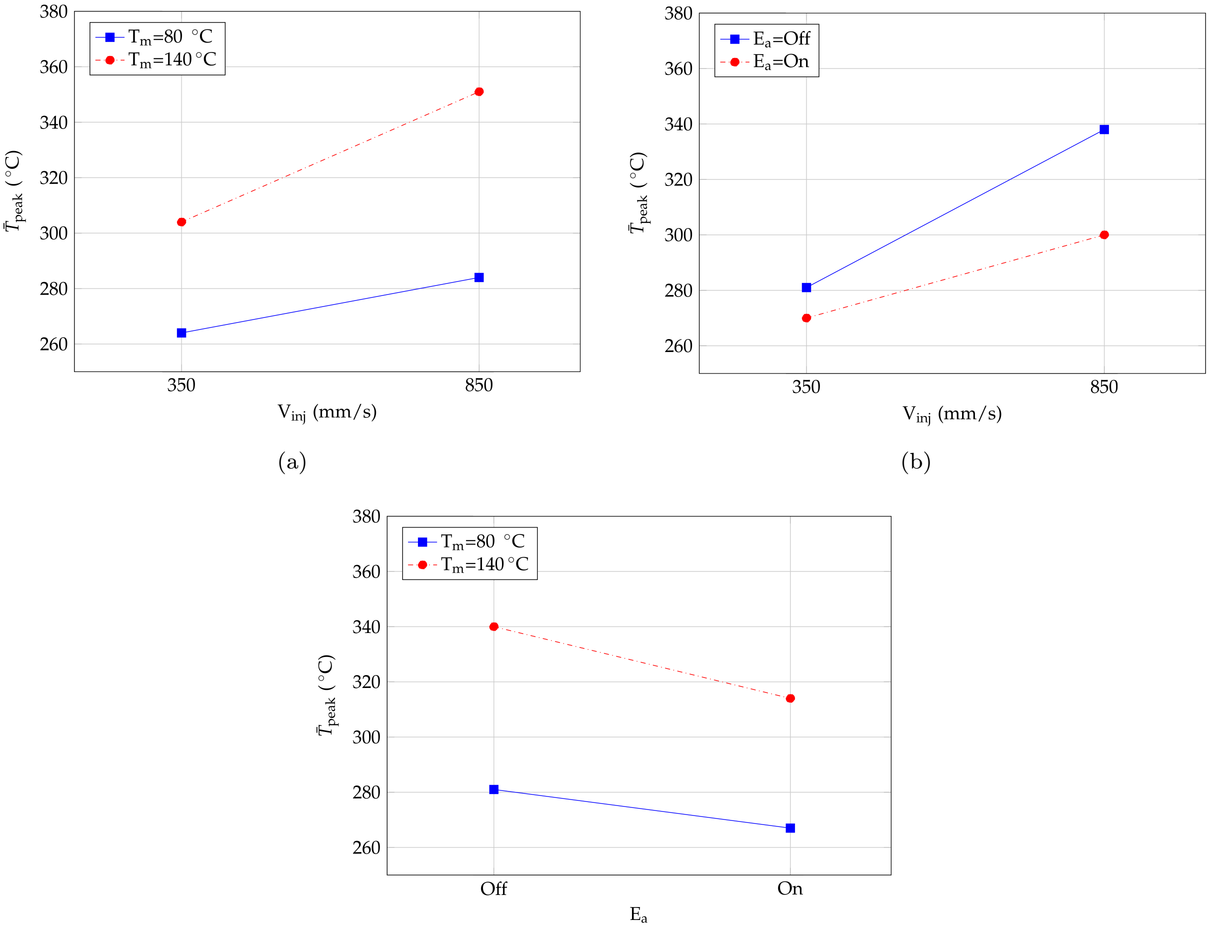
cluding all the main factors and their interactions. The ANOVA results of the experimental plan indicate that all of the main factors are significant (Tab. 6).

Table 6: ANOVA results for the experimental plan

Source	**SS**	**MS**	**F**	**P**
T_m	16757.7	16757.7	2372.97	0.000
V_{inj}	6594.2	6594.2	933.77	0.000
E_a	2297.9	2297.9	325.40	0.000
$T_m \cdot V_{inj}$	1198.5	1198.5	169.71	0.000
$T_m \cdot E_a$	199.9	199.9	28.30	0.000
$V_{inj} \cdot E_a$	536.0	536.0	75.90	0.000
$T_m \cdot V_{inj} \cdot E_a$	87.1	87.1	12.33	0.003
Error	113.0	113.0	7.1	

3.1 Effect of air evacuation

Interestingly, it was observed that the effect of applying vacuum venting before the injection, resulted in a significant reduction of the melt flow temperature as shown in Fig. 5a. In particular, when evacuating the air from the cavity the average value of the flow front temperature decreases by 7%. The air trapped inside the cavity is subjected to a rapid compression between cavity walls and the polymer melt injected at high speed. This phenomena is particularly relevant in small cavities, typical of μIM applications. The heat that is produced increases both the temperature of the flow front and the mould temperature. Therefore, when applying vacuum venting the consequent reduction of the melt and mould temperature should be considered, as it directly affects the thermal gradient between the melt and the mould. This effect can be particularly significant for the μIM process, in which mould temperature plays a fundamental role in determining the filling length of the polymer in narrow cavities and micro/nano features. In particular, a lower temperature, and thus a higher viscosity of the melt, can significantly hinder the filling of micro cavities even when applying high values of holding pressure.



(a) (b)

(c)

Fig. 6: Interaction plots of (a) injection speed and mould temperature, (b) injection speed and air evacuation, (c) mould temperature and air evacuation.

3.2 Effect of injection speed and mould temperature

By increasing the injection speed from 350 to 850 mm/s the temperature of the flow front increases by +12% on average (Fig. 5b). This effect is related to the higher shear rates that characterise the flow and produce a higher viscous heating.

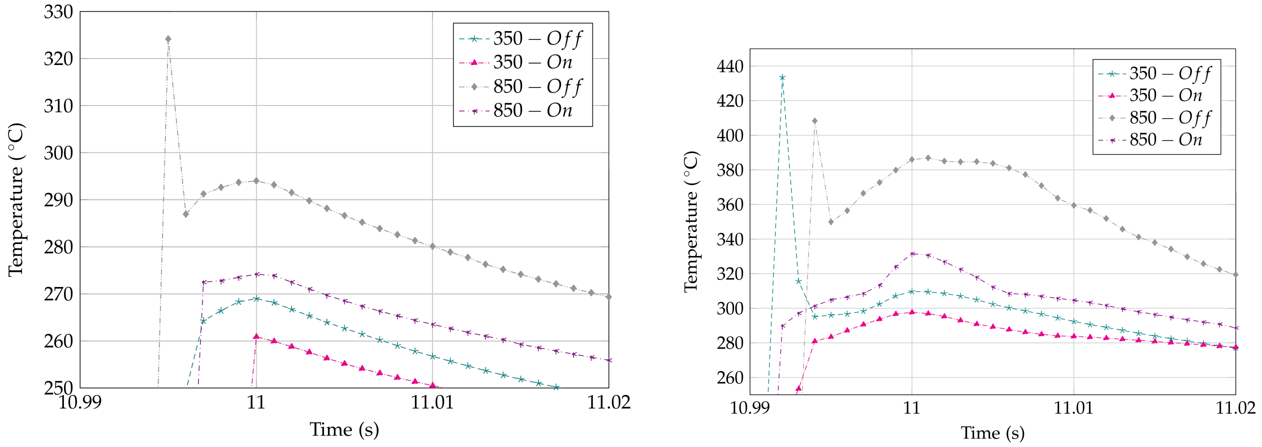
The main effect of the mould temperature on the melt flow temperature is reported in Fig. 5c. This is related to the thermal flux between the mould and the polymer melt. By increasing the mould temperature from 80 °C to 140 °C the temperature at the flow front increases from 274 °C to 327 °C (+19% on average).

3.3 Effect of first order interactions

To completely understand the influence of process parameters on the temperature at the flow front, the effects of first order interactions have to be considered as shown by the analysis of variance (Tab. 6).

When the polymer is injected at a higher mould temperature, the effect of injection velocity is more evident (Fig. 6a). This is related to the thermal conduction rate of the mould. Indeed,moulding at high value of injection speed, the air compression rate is greater causing higher temperature rise. This effect is amplified by higher mould temperature, at which the thermal gradient between the mould and the polymer is smaller and so the heat conduction.

The interaction between the injection speed and the evacuation of air from the cavity is reported in Fig. 6b. When vacuum venting is not applied, at a high value of injection speed the air in the cavity is compressed at a higher rate thus the increase of the flow front temperature is greater. The evacuation of the air from the cavity contrasts the rapid compression and as a result



(a) (b)

Fig. 7: Experimental temperature data for different moulding conditions at (a) 80 °C and (b)140 °C. The maximum standard deviation for the average value is 4.02 °C.

it lessens the increase of the polymer flow front temperature.

As shown in Fig. 6c , the effect of applying vacuum venting is more significant when moulding at a higher mould temperature, both for low and high injection speeds. This is more evident in Fig. 7, which shows the experimental average temperature data for the different moulding conditions at 80 °C (7a) and 140 °C (7b). At lower mould temperature, the pressure drop during the filling phase is higher, due to the higher viscosity of the polymer and to the thicker solidified layer. Therefore, the melt flow front velocity decreases according to the polymer compressibility. In fact, as reported in Fig. 7a, when injection moulding at lower value of mould temperature and without applying vacuum venting, the burn effect, which is caused by the rapid compression of the air ahead of the polymer flow front, occurs only at high value of injection velocity. Conversely at high value of mould temperature (Fig. 7b) and without cavity air evacuation, the burn effect occurs for both high and low value of injection speed causing an increment of the mould surface temperature.

4 Conclusions

Cavity air evacuation has been introduced in μIM with the intent to further enhance features replication accuracy. Nevertheless, the effect of this auxiliary technology has produce conflicting results, as reported in section 1. The negative effect in applying vacuum venting in μIM has been attributed to the removal of warm air from the cavity, which decreases the mould temperature during the process [15]. However, this hypothesis has not been demonstrated yet. In this work the effect of cavity air evacuation was experimentally investigated, monitoring mould and polymer temperature evolution during the micro injection moulding process by means of a high speed infrared camera and a sapphire window which forms part of the mould wall. The results of the experimental tests showed that when evacuating the air from the cavity the average value of the measured temperature decreases by 7%. In particular, when applying vacuum venting the consequent reduction of the flow front temperature should be considered, as it directly affects the thermal gradient between the mould and the melt. It was observed that the effect of applying vacuum venting is more evident when moulding at a higher mould temperature, both for low and high injection speed. These results are a novel contribution with respect to the state of the art. The main effect of injection speed and mould temperature are significant as well. In particular, by increasing the injection speed from 350 to 850 mm/s the temperature of the flow front increases by +12% on average due to the higher shear rates that characterise the flow and produce a higher viscous heating. The main effect of the mould temperature on the melt flow temperature is related to the thermal flux between the mould and the polymer melt. By increasing the mould temperature from 80 °C to 140 °C the temperature at the flow front increases by +19% on average. Interestingly, it was observed that moulding at high value of injection speed, the air compression rate is greater causing higher temperature rise. This effect is amplified by higher mould temperature, at which the thermal gradient between the mould and the polymer is smaller and so the heat conduction. Moreover, at lower mould temperature, the pressure drop during the filling phase is higher, due to the higher viscosity of the polymer and to the thicker solidified layer. Therefore, the melt flow front velocity decreases according to the polymer compressibility. This effect can be particularly significant for the micro injection moulding process for which it is well-known that the temperature plays a fundamental role in determining the filling length of the polymer in micro/nano features."

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