Materials Research Proceedings 41 (2024) 2686-2694 https://doi.org/10.21741/9781644903131-294

Analysis of the effect of draft angle and surface roughness on ejection forces in micro injection molding

MACIARIELLO Francesco[1,a*], LUCCHETTA Giovanni[1,b] and SORGATO Marco[1,c]

[1]Department of Industrial Engineering, University of Padova, via Venezia 1, 35010, Padova, Italy

[a]maciariello.francesco@gmail.com, [b]giovanni.lucchetta@unipd.it, [c]marco.sorgato@unipd.it

Keywords: Micro Injection Molding, Draft Angle, Surface Roughness, Ejection Force, Demolding

Abstract. Minimizing ejection forces is a crucial challenge in micro injection molding to prevent component damage during demolding. This research investigates the effects and interactions of draft angle, surface roughness, mold temperature, and holding pressure on the ejection force in a small, box-shaped component made from polypropylene (PP) and cyclic olefin copolymer (COC). A piezoelectric force sensor, integrated into the ejection tray of the mold, was used to measure the peak ejection force. The results indicate a significant influence of polymer type on ejection force, with PP exhibiting a 26% lower peak ejection force than COC. The draft angle consistently reduced demolding forces. Strong interactions were observed between mold temperature, surface roughness, and polymer type. Specifically, an increase in mold temperature led to an 88% increase in ejection force for COC, while resulting in a 63% decrease for PP. For PP, the optimal ejection force was measured at a surface roughness (Sa) of 0.095 µm, while for COC, a continuous decrease in ejection force was measured with decreasing surface roughness.

Introduction

Micro injection molding (µIM) is a key technology in the production of small, high-precision thermoplastic components for applications in the biomedical, microelectronics and automotive industries. From the miniaturization of components and molds arises the necessity for better understanding of the µIM process, especially regarding the demolding phase. During separation of the part from the mold, ejector pins can produce concentrated stresses that lead to deformation and surface defects in the component [1], [2]. Management of ejection forces is therefore critical to ensure defect-free production [3].

The correct replication of the mold cavity is influenced by many process parameters and by the correct design and fabrication of the injection mold itself [4], [5]. Of the variables that have an impact on the molding process, mold temperature (Tm), holding pressure (Ph), draft angle and surface roughness have been shown to have the greatest effect on the ejection forces [6]-[10]. A draft angle between 1° and 3° is commonly used to facilitate demolding. A core surface roughness between 0.092 µmRa and 0.212 µmRa has also been shown to result minimal ejection forces in cylindrical components [11]. As it is often the case in micro injection molding, the geometrical properties of the mold are constrained by aesthetical and functional requirements of the molded component. When geometrical parameters cannot be altered, ejection forces can be mitigated via the correct selection of process parameters. While holding pressure and mold temperature have been shown to influence the ejection force, their effect is not easily predictable and seems to be dependent on polymer selection. Pontes et al. [8] found a reduction in ejection forces with the increase of Tm for PP and PS. They also found a value of Ph that maximizes ejection forces. Griffiths et al. [12] found an increase in ejection forces when increasing Tm and Ph in COC. Bhagavatula et al. [13] found on the other hand a decrease in force with pressure when molding HDPE and HIPS.

A deeper understanding of the effect of process and geometrical parameters on ejection forces is needed, especially for the accurate reproduction of micro-components. Beyond considering the main effects of the studied variables, it is essential to understand their interactions, as these can significantly affect peak ejection forces.

Materials and Methods

Two distinct thermoplastic materials were used in this analysis: TOPAS 5013-10L cyclic olefin polymer (COC) and ISOPLEN A H F polypropylene (PP) by Sirmax. Both polymers are widely used in biomedical and mechanical applications [14]. The materials' thermal properties were evaluated using Differential Scanning Calorimetry (DSC) on a TA Instruments DSC Q200. Rheological properties were evaluated on an oscillatory rheometer TA Instruments ARES. The DSC tests for PP spanned a temperature between -40°C and 250°C, with a heating rate of 10°C/min, whereas for COC the range was 0°C to 360°C, also with a heating rate of 10°C/min. Rotary rheometer tests were conducted at 185°C, 200°C and 215°C for PP and 220°C, 240°C and 260°C for COC.

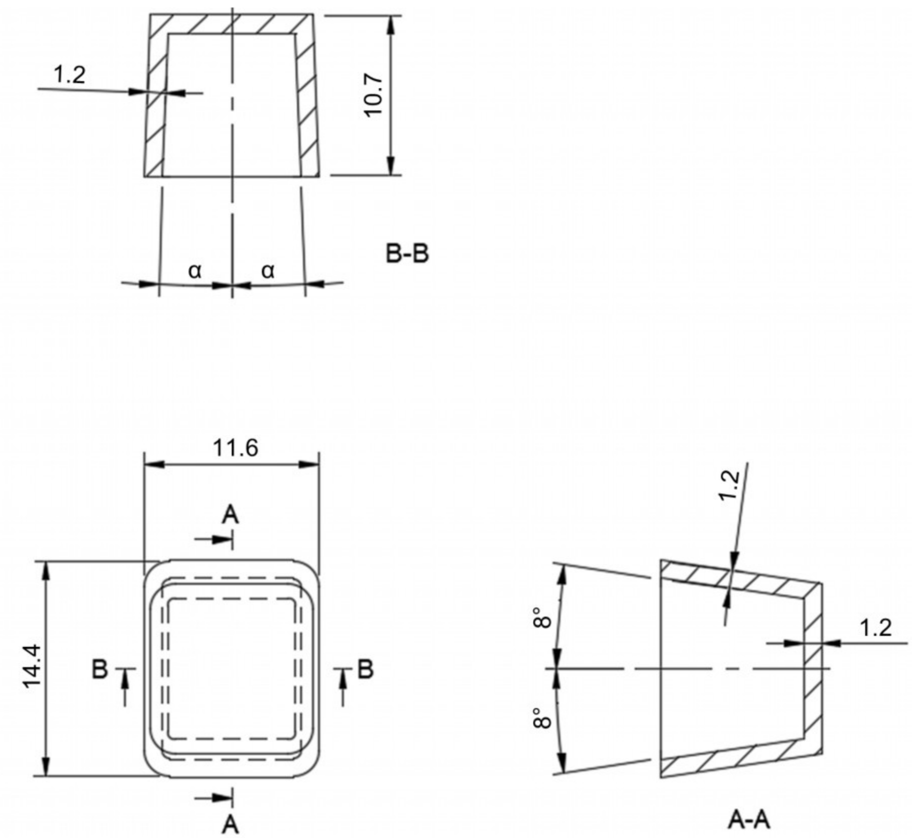

Figure 1:technical drawing of the molded component, where α represents the variable draft angle.

A small box-shaped component was designed for the experiments, measuring 14.4 x 11.6 x 10.7 mm with a wall thickness of 1.2 mm. Of the four lateral faces of the mold core, only two underwent surface treatment and had variable draft angle ranging between 0.25°, 1°, 2°. The non-treated faces had an 8° draft angle and a smaller surface area to minimize their impact on ejection forces. A technical drawing of the component is shown in *Fig. 1*, where α indicates the variable draft angle.

The samples were injected from the center of the upper face to ensure optimal and symmetrical filling of the cavity. This design prevents the formation of weld lines and air inclusions. It also minimizes the pressure loss during packing and holding, thereby reducing deformation due to uneven shrinkage. These design assumptions were validated through process simulations using Moldflow Insight 2019.

The mold used for the experiments was based on a Hasco modular system. Special attention was placed on the design of the cooling system to obtain a uniform temperature in the cavity. Six cylindrical ejector pins, each with a 1 mm tip diameter (Hasco code Z441), were placed symmetrically around the component's perimeter to balance the ejection force. The even distribution of the ejectors is chosen to limit part deformation during the demolding phase [15], [16]. The ejectors' base was placed on a distribution plate to transfer the total ejection force to the piezoelectric sensor in the ejection tray, as shown in *Fig. 2*.

Molding was performed on a Wittmann Battenfeld Micropower 15, a state-of-the-art micro injection molding machine equipped with a 15-ton clamping unit and an advanced control system that enables precise adjustment of process parameters. Ejection forces were measured using a Kistler 9223A piezoelectric force sensor, interfaced to a Kistler 5865A10 measuring and control unit with a sampling frequency of 60 kHz.

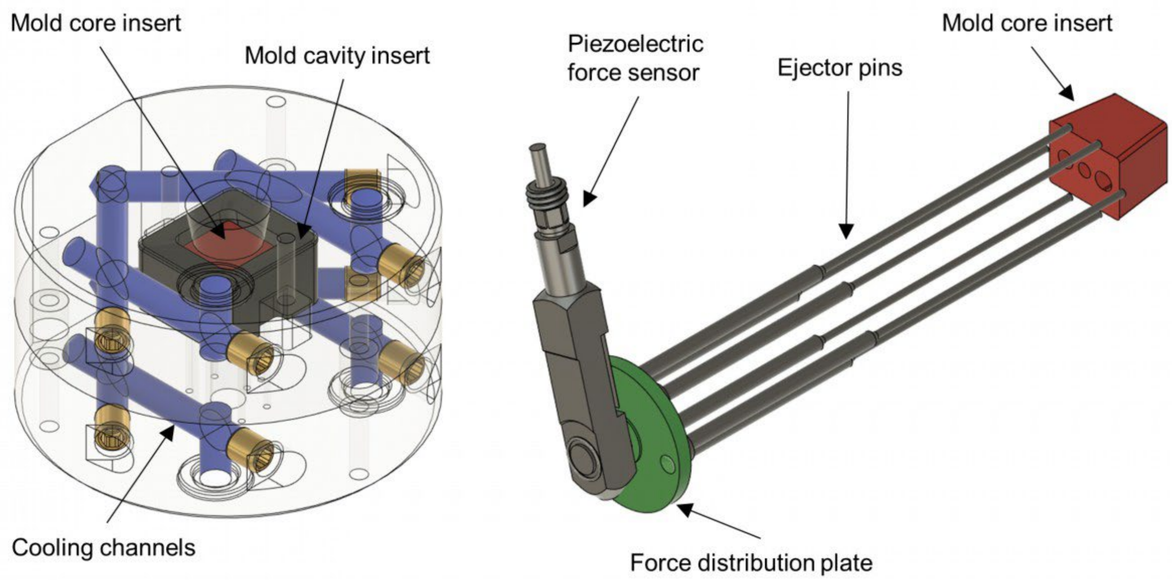

Fig. 2: mold design details: (a) cooling system, (b) ejection system.

The different roughness profiles of the mold core inserts were achieved through manual polishing, resulting in three finishes (fine, medium, coarse), ranging between 0.01 µmRa and 0.3 µmRa. In this range, minimum ejection forces should be measured according to previous research [10], [11], [17]. The manual polishing procedure was performed by a trained operator to reduce process variability.

Surface roughness of the treated faces was then measured with a Sensofar optical profilometer equipped with Nikon TU Plan Flour 20x lenses. The scanned area consists of two rectangular sections measuring 1.5 x 5 mm, located on the top left corner of the insert's face. Both polished faces of each mold insert were scanned. A 3D printed support was used to facilitate the horizontal positioning of the faces during analysis. The data was processed in the SensoVIEW 1.9.2 software. A plane form removal filter was applied in accordance with ISO 25178 to eliminate any error due to uneven placement of the component. A short filter (λ_s) of 2.5 µm was applied to all scanned surfaces. A long filter (λ_c) of 80 µm was applied to the coarse and medium finished surfaces, while a 25 µm filter was applied to the fine finished surfaces before measuring the areal surface

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roughness. Ra values were determined in accordance with ISO 4288, ISO 4287, and ISO 13565-2.

In addition to studying surface finish and draft angle, the research also examined the effects of holding pressure (Ph) and mold temperature (Tm) on ejection forces. For each polymer, two levels of packing pressure and mold temperature were chosen, covering the recommended processing window for each material, as shown in Table 1. All other process parameters, except for melt temperature (T_b), were standardized for both polymers, as detailed in Table 2.

For every combination of the four study parameters, the peak force was measured. The data was then analyzed to find main effect and first-order interaction of the variables.

Table 1: Variables and levels tested in the study for PP and COC.

Variable Level	Draft angle [°]	Roughness Sa [µm]	Tm COC [°C]	Tm PP [°C]	Ph [bar]
1	0.25	0.015	105	35	50
2	1	0.095	125	60	100
3	2	0.278	\\	\\	\\

Table 2: Melt temperature, injection speed, packing time and cooling time for the µIM experiments.

Parameter	Melt temperature [°C]	Injection speed [mm/s]	Packing time [s]	Cooling time [s]
PP	240	100	5	12
COC	320	100	5	12

Results and discussion

Polymer analysis: The thermal properties of the studied materials, and the fitted Cross-WLF constants (Eq. 1 and Eq. 2) are shown in Table 3.

$$\eta = \frac{\eta_0}{1 + \left(\frac{\eta_0}{\tau^*}\dot{\gamma}\right)^{1-n}} \tag{1}$$

$$\eta_0 = D_1 \, exp\left(\frac{-A_1(T - T^*)}{A_2 + (T - T^*)}\right) \tag{2}$$

The two polymers present markedly different flow behavior. The Melt Flow Index (MFI) of COC is almost four times greater than that of PP.

Table 3: thermal properties of the studied polymers and Cross-WLF model constants.

Property	PP	COC
Melt temperature [°C]	168	//
Crystallization temperature [°C]	120	//
Glass transition temperature (T_g) [°C]	-13	137
MFI (ISO 1133) [g/10 min]	12 (230°C, 2.16kg)	47 (260°C, 2.16kg)
n []	0.269	0.329
τ* [Pa]	11700	50900
T* [K]	260	410
D1 [Pa·s]	331777	96633
A1 []	1072	2491
A2 [K]	41220	50111

Roughness analysis: Surface roughness measurements of the mold's core show good repeatability of the manual polishing procedure. The three surface finishes range between 0.015 µmRa and 0.275 µmRa. Surface roughness measures expressed as S_a, S_{pk}, S_{vk}, and R_a are shown in Table 4. For the remainder of the paper, roughness values will be indicated in terms of S_a [µm].

Table 4: Roughness of the polished core faces.

Roughness level	R1 (smooth)	R2 (medium)	R3 (coarse)
S_a [µm]	0.015	0.095	0.275
S_{pk} [µm]	0.020	0.100	0.285
S_{vk} [µm]	0.025	0.115	0.350
R_a [µm]	0.016	0.098	0.270

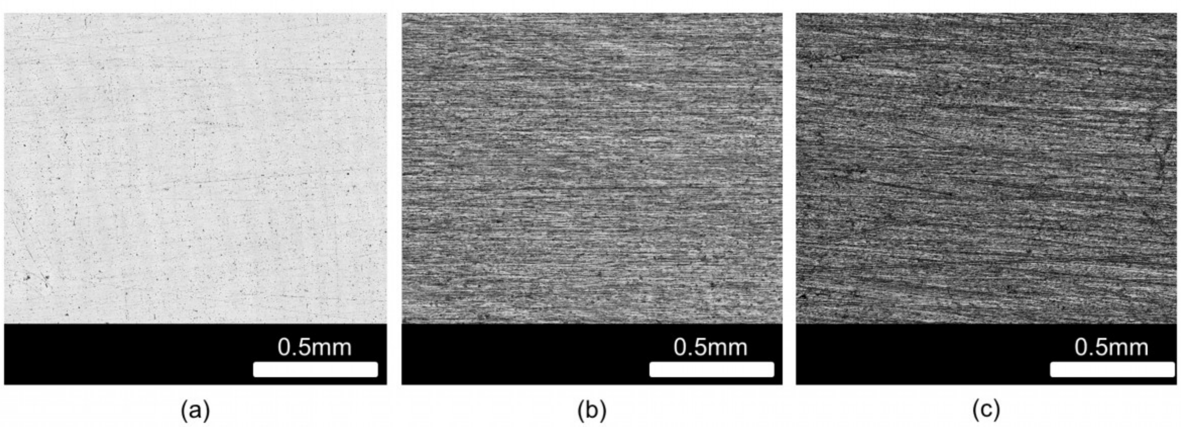

Figure 3: Image of the mold's core surface (a) R1 (b) R2 (c) R3.

Micro injection molding results: The results from the Analysis of Variance (ANOVA) applied to the µIM experiments show that all the main factors investigated have a significant impact on peak ejection force (Table 5). Many of the first-order interactions of the studied variables are also statistically significant. Plots showing the effect of the studied parameters on peak ejection force for PP and COC are shown in *Fig. 3*.

Table 5: effect of the studied variables on peak ejection force, ANOVA results.

Source	DF	Adj MS	F-Value	P-Value
Draft angle	2	3005.4	107.96	0.000
Roughness	2	2404.3	86.36	0.000
Tm	1	500.8	17.99	0.000
Ph	1	1586.5	56.99	0.000
Polymer	1	10720.4	385.08	0.000
Draft angle * Roughness	4	195.8	7.03	0.000
Draft angle * Tm	2	859.6	30.88	0.000
Draft angle * Ph	2	194.3	6.98	0.001
Draft angle * Polymer	2	34.5	1.24	0.291
Roughness * Tm	2	1164.7	41.84	0.000
Roughness * Ph	2	132.9	4.77	0.009
Roughness * Polymer	2	5307.5	190.65	0.000
Tm * Ph	1	4.7	0.17	0.683
Tm * Polymer	1	68640.1	2465.59	0.000
Ph * Polymer	1	17.2	0.62	0.432
Total	359			

Effects of polymer selection: The experimental data underscores the critical role of polymer selection in determining the ejection force. In COC, a 11.5 N higher mean peak ejection force was measured compared to PP. The two polymers also exhibit a different response to some of the other variables. Consequently, the following results are presented separately for cyclic olefins and polypropylene.

Effects of draft angle and packing pressure: Both materials exhibited a similar response to draft angle and packing pressure variations. Increasing packing pressure from 50 bar to 100 bar produced an increase in peak ejection force of 13.0 N in COC and 4.6 N in PP. An increase in packing pressure can result in a reduction of through-thickness shrinkage [8], and therefore in an increase in contact pressure between component and mold core. The higher contact pressure increases the frictional forces during separation and ejection forces increase. An increase in draft angle systematically reduced the ejection force for both polymers. This reduction is greater at lower draft values. An increment from 0.25° to 1° resulted in the reduction in ejection force by 6.7 N in COC and 6.9 N in PP. The further increase of draft angle to 2° only produced a decrease in peak ejection force of 2 N in COC and 1.9 N in PP.

Effects of mold temperature: Increasing the mold temperature has opposite effects on the two materials. The increase in T_m to 60°C results in a 29.8 N reduction in ejection force for PP, when compared to the ejection force at 35°C. If cycle time is kept constant, an increase in mold temperature leads to an increase in part surface temperature. Higher temperatures lead to a reduction in component's stiffness and therefore to a reduction in ejection force [8]. In the case of COC, increasing mold temperature from 105°C to 125°C produces a 26.8 N increase in peak ejection force. Similar results were obtained by Griffiths et. Al. [12] when printing Topas 5013 COC at 70°C and 130°C. The increase in ejection force at higher Tm may be the result of better mold core replication. The different response of the two materials to changes in mold temperature is the result of the different thermal and rheological properties of the polymers. Topas 5013 have a high heat deflection temperature (HDT) of 130°C and a high shear modulus that does not decrease until 10°C below Tg. Therefore, the increase in ejection force with mold temperature is the consequence of better tool replication and high stiffness of the polymer. In the case of PP, the effect of better replication is compensated by the reduction in material rigidity at higher mold temperatures. A higher Tm could then be useful to ensure correct replication of the mold, lower ejection forces, and increase crystallinity and tensile properties in PP components [18].

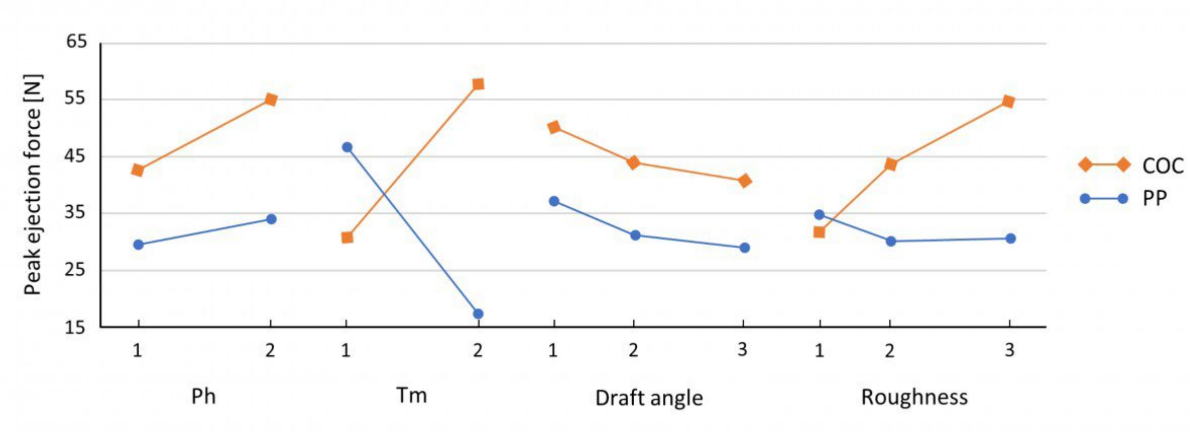

Fig. 4: main effect plot for the studied parameters.

Effects of surface roughness: PP and COC responded differently to variations in surface roughness. COC showed a consistent increase in ejection force with the increase of Sa. The minimum peak force was measured at 0.015 µmSa with a value of 31.6 N. Increasing S_a to 0.095 µm resulted in an increase in force by 12.9 N, and further increasing Sa to 0.275 µm produced an additional 10.9 N increase in peak ejection force. This trend contradicts previous studies in which a minimum in ejection force was observed within the roughness range studied. In the case of Polypropylene, the minimum ejection force of 30.6 N was measured for a surface roughness of 0.095 µmSa. The maximum ejection force of 35.2 N was measured at the minimum core roughness value, while a force of 31.5 N was measured when molding on the roughest core. This data is consistent with previous studies [11] and shows the existence of an optimal surface roughness for minimizing ejection forces in PP.

As surface roughness decreases, the frictional forces due to mechanical interlocking between the mold and the plastic component decrease, while adhesion forces increase. This was found to lead to an optimal surface roughness where ejection forces are minimized [11]. In the case of COC, the steady decrease in peak ejection force even at very low surface roughness suggests the dominance of mechanical interlocking forces over adhesion forces. To reduce ejection forces for COC components molded on uncoated steel molds, it is then recommended to reduce surface roughness to values between 0.015 µmSa and 0.1 µmSa.

Summary

This study provided a comprehensive analysis of the impact of draft angle, surface roughness, mold temperature, and packing pressure on ejection forces in micro injection molding, utilizing polypropylene (PP) and cyclic olefin copolymer (COC). Key findings demonstrate that polymer selection significantly affects ejection forces, with PP exhibiting a 26% lower peak ejection force compared to COC. Additionally, an increase in mold temperature resulted in an 88% increase in ejection force for COC, and a 63% decrease for PP. Surface roughness also had a key role, with the ejection force for PP reaching a minimum at a roughness value (Sa) of 0.095 µm, while COC showed a continual decrease in ejection force with decreasing surface roughness, without an optimum point. These findings underline the complex interactions that exist between polymer selection, geometrical and process parameters, showing the importance of considering material-specific responses when optimizing the injection molding process.

In conclusion, this research contributes to a deeper understanding of the µIM process, particularly in terms of managing ejection forces. These findings can be helpful in guiding future mold designs and process optimizations, especially in micro injection molding.

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