Investigation of Warpage and Tolerances in Injection Moulding Components Based on Simulation and Experimental Validation / Garlaschelli, G.; Gherardini, F.; Malagola, S.; Leali, F.. - (2022), pp. 342-353. (2nd International Conference on Design Tools and Methods in Industrial Engineering, ADM 2021 ita 2021) [10.1007/978-3-030-91234-5_35].

Springer Science and Business Media Deutschland GmbH

Investigation of Warpage and Tolerances in Injection Moulding Components based on Simulation and Experimental Validation

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Abstract. This paper presents a systematic approach to model and simulate the influence that the variation of process parameters has on the final quality of an injection moulded component. In the first phase, we define a multi-steps procedure to develop a reliable digital model of the injection moulding process by the fine-tuning of the part cavity and the mould elements (e.g. detail simplification, discretization and mesh density, elements modelling, etc.) using real data as validation. In the second phase, we investigate the correlation between selected process parameters and the final tolerances of the moulded component, based on a Design of Experiments. As a case study, we selected the body of a mass airflow sensor for an automotive high performance engines, made of polybutylene terephthalate reinforced with glass-fibre, which presents roundness issues on functional features. The effects of the injection velocity and packing pressure on the deformation of the component are investigated, identifying the best combination of their values that leads to compliance with the roundness tolerances on its functional features. The injection moulding Computer Aided Engineering (CAE) software Moldex3D (CoreTech) is used to run the simulations, and the results are finally validated by comparing the experimental data obtained from the injection moulding machine that produces the component.

Keywords: Simulation-based Design Approach, Design of Experiments, Injection Moulding, Warpage, Tolerances.

1. Introduction

The injection moulding (IM) manufacturing process of a polymeric component leads to a final shape that differs from the ideal one due to a large number of parameters that rule the manufacturing process itself. Many works deal with the study and optimization of IM parameters [1-3] to comply with the dimensional and geometric tolerances on functional elements of injection moulded components [4-7]. On the one hand, IM simulations [8-9] are used in industries mainly for preliminary validations and first attempts in filling the cavity but, on the other hand, the most recent trends show that researchers are moving towards smart manufacturing [10-11] and digital twin approaches [12-13].

Among the models required in the digital twin approach, the main one is about the simulation of the injection process, considering all the fluid-dynamic and thermal effects. Computer Aided Engineering (CAE) applications for IM are widespread and work correctly if the starting model of the mould system is reliable.

In this work, we want to carry out an in-depth study of the correlation between the simulated mould model and the real mould used within the IM machine, thanks to a close alignment between the simulated data and the real ones. In the modelling phase, we investigate the effects of the number of mesh elements, of the modelling of the elements of the cooling system as well as its mesh elements, up to convergence on target values [14-16]. Once the model has been calibrated and validated with experimental tests, this can be used to correlate the process parameters with the deformations (warpage) of the part, and therefore to further define new values that reduces the deformation. In order to tackle this task, a Design of Experiments (DOE) [17-19] is applied. The study does not consider the influence of the characteristics of the material (which is kept unchanged with respect to current manufacturing process and considered as an input to the analysis) as well as the design choices that led to the creation of the mould. The only fields of action available are the process parameters that could be easily modified in production.

The paper is structured as follows: Section 2 presents the method, Section 3 presents the case study, Section 4 highlights the results and Section 5 closes the paper.

2. Method

The design approach to model, simulate and study the IM process consists of two main phases. In the first (i.e. modelling phase), the system elements are modelled, simplified and discretized as follows:

1) Defeaturing of the part: Before the mesh creation, the features that may have a negative influence on the quality of the mesh, or are not relevant for the goal, are eliminated from the model.

2) Modelling and discretization of the mould elements: Before creating the whole mesh of the mould system, the mould elements needs to be simplified and preliminary evaluation of the mesh density of these elements are required, in particular, of the entire mould and the cooling system.

3) Definition of mesh size and density: It is a preliminary phase in which some considerations on the discretization of the domain were made. However, the mesh convergence eliminates the influence of discretization from the deformation results, allowing an objective assessment of the correlation with the process parameters subjected to variation. These assessments have been made considering the available computing power with respect to the mesh size of the part.

All these steps are validated by comparing the simulations with IM experiments.

In the second phase (systematic simulation), the developed model is finally used as input to CAE simulation~~s~~, to correlate the IM parameters to be investigated according to a factorial plan (DOE). The parameters as well as their values involved in the DOE are previously selected thanks to experience or a screening phase. In this way a full factorial design involving a low number of factors, each with a high number of levels (i.e. values) can be performed. This is important to simulate and analyse the correlation between inputs (i.e. factors) and outputs (i.e. responses).

3. Case study

The component selected as a case study is the body of a mass airflow sensor (mass flow meter) for an automotive high-performance engine. The complexity of the geometry (Fig.1) is mainly due to the presence of the housing of the sensor for detecting the intake airflow. The component is made of polybutylene terephthalate (PBT) reinforced with 30% glass fibre. PBT has excellent mechanical (i.e. stiffness and toughness), thermal, tribological, and aesthetic characteristics. It also absorbs a very low moisture content, so the moulded parts present~~ a~~ high dimensional stability. The runner has 3 equally spaced gates (Fig.1, left), and a cooling system with a central baffle (Fig.1, right). The geometry of the part and the mould are considered design inputs and they cannot be changed.

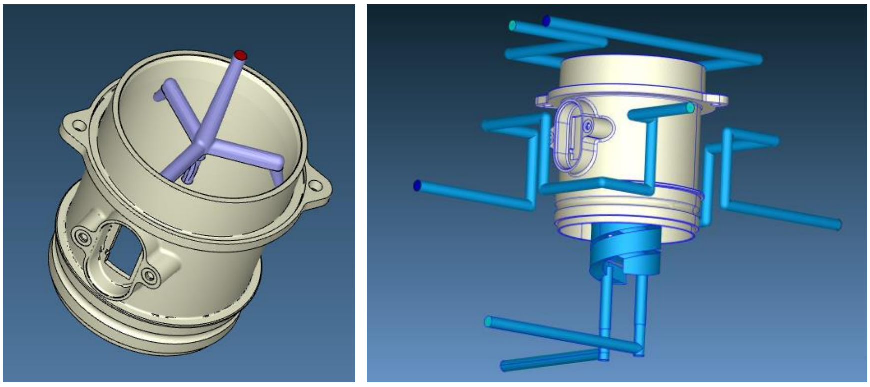

Fig. 1. Runner geometry and location (left); 3D model of the cooling system in Moldex3D (right).

In the current manufacturing process, the design specifications are generally achieved, satisfying most of the dimensional and geometric requirements established in the design phase but some latent defects occur due to local deformations that causes roundness (circularity) issues in particular on the side opposite to the gates location. On the other hand, we selected this case study thanks to the high level of knowledge of the component and the manufacturing process, and the large amount of data available. This allows for accurate evaluations on the variation of the process parameters and an experimental validation of the simulation results.

4. Results

4.1 Modelling phase

In the first phase, we modelled the part according to the part defeaturing, simplifying the mould elements, setting the mesh size and density, etc. To achieve the mesh convergence, we had to run a reference simulation many times. To this aim, we set the values of the IM parameters as in the real process. In the following text, we refer to them as “initial parameters” as they represent the starting point of the DOE investigation. The values of parameters are listed in Table 1. Among them, we focused on two parameters that will be further investigated in the second phase: the injection velocity, set constantly to 80 mm/s in the first part of the injection cycle (up to 62% of the injection stroke), and then reduced to 10 mm/s in the second part. The packing pressure is set constantly to the value of 85 MPa for 15 s.

Table 1. Initial process parameters.

Parameter	value	Parameter	Value
Melt temperature (°C)	265	Max. Pack. pressure (MPa)	85
Mould temperature (°C)	85	Cooling time (s)	30
Max. Inj. pressure (MPa)	175	Mould-open time (s)	15
Injection volume (cm^3)	153.562	Eject temperature (°C)	170
Packing time (s)	15	Cycle time (s)	60.59

Defeaturing of the part (1). Before creating the mesh, the features of the component are analysed to remove unnecessary details. For this purpose, the text and symbols were eliminated, since these are in relief on the component surface and present reduced thickness compared to the one of the main body. Then, we analysed the dress-up features of the component, such as chamfers and fillets, which cannot be simplified for their importance in the manufacturing process. We maintain all fillets above 0.2 mm, which positively affect the injection of the molten polymer and avoid stress localization.

Modelling and discretization of the mould elements (2). The mould elements such as runners, cooling channels, inserts, etc., may require to be simplified in their geometry and then discretized by an adequate number of mesh elements. About the mould base, as there was no appreciable difference in reproducing all its external dimensions and shape, it was modelled with a simple prism, which returned fully comparable results. Similarly, we simplified the two mould inserts, which are placed in a not-critical area (i.e. the sensor housing), creating holes corresponding to their external diameter.

Besides, the mesh size of the cooling system is investigated. The analysis of the cooling efficiency (i.e. the parameter that establishes the percentage of thermal energy exchanged by each component of the cooling system) of the various parts of the cooling system shows that the central baffle has the most important role in cooling the molten material inside of the cavity (Fig. 2, left). The discretization of the boundary layer of the cooling channels may have a significant influence on the cooling performance. A recommended number of elements (at least 3 layers of prismatic elements) is suggested by Moldex3D software. Therefore, four different configurations of mesh elements in the cooling system were investigated to check whether there was a real advantage in deviating from the number of elements recommended by the software, as well as in increasing the number of mesh elements in the baffle (4 mesh sizes). A simulation was carried out with each of these mesh models, using the initial values of the process parameters (Table 1). The results of the four simulations show how increasing the number of elements of the boundary layer (from 2 to 4 elements, with meshes 2 and 3 kept at the recommended value equal to 3) does not lead to a consistent difference in the responses, i.e. the number of Reynolds along the cooling system and the cooling heat flux. The maximum value of the number of Reynolds assumes the following values: 8.825 e^{+04}; 8.806 e^{+04}; 9.000 e^{+04} in the changes of direction of the channels. The minimum value of the number of Reynolds assumes the following values: 3.485 e^{-09}; 2.174 e^{-07}; 2.090 e^{-11}; 1.586 e^{-11} in some critical areas of the baffles, i.e. those in which stagnation phenomena of the cooling water occur (in the upper part and in correspondence with the inlet and outlet areas of the baffle). In these areas, the Reynolds number also varies by orders of magnitude as the mesh varies. However, the differences, in terms of exchanged heat flow, between the various simulations are very limited and are concentrated in the upper area of the baffle. In these areas, the low velocity of the water (used as refrigerant fluid) causes the refrigerant to reach a high temperature, but have a little influence for the study of cooling effect. In all the other regions, the results of the four simulations are absolutely comparable in terms of heat exchanged. As there was no advantages in refining the mesh size of the baffle, as well as there was no advantage in using a number of boundary elements higher than the recommended value (3), we set the lowest number of elements for the cooling system mesh.

Furthermore, we checked the impact on the results of using a simplified model of the baffle instead of its real geometry. Moldex3D offers the possibility of modelling complex parts of the cooling system in a simplified shape, through the management of a few parameters. This simplified model (Fig. 2, right) returns a reliable result regarding the deformation of the part, as demonstrated by the experimental validation, but presents a different percentage of thermal energy subtracted from the cavity. The difference in the total percentage of energy removed from the baffle with respect to the totality of the cooling systems is 31% (real geometry) vs 25% (simplified geometry). For this reason, the real geometry of the baffle was used for the second phase of simulation.

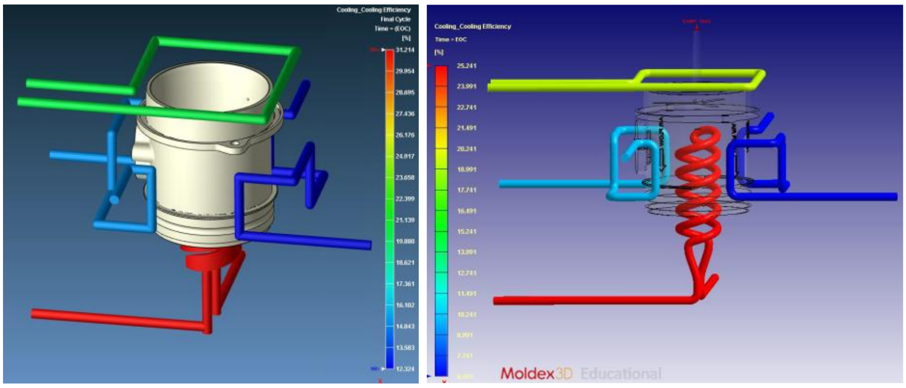

Fig. 2. Cooling efficiency of the cooling system: the real baffle (left); the simplified one (right).

Mesh size and density (3). We finally generated a surface mesh for the cavity (part), the runners and the cooling system. In particular, the small-sized fillets were discretized with at least two surface elements, to ensure that they kept characteristics closer to those of a fillet than to those of a chamfer. For the preliminary phase of the study, aimed at identifying the most suitable mesh size and density to achieve the goal, four different meshes were created, always doubling (indicatively) the number of total volume elements. Mesh 1: 829,140 elements; Mesh 2: 1,590,440 elements; Mesh 3: 4,049,484 elements; Mesh 4: 9,552,816 elements. To compare the mesh density, we ~~The comparison of the mesh density~~ required to identify a parameter to assess mesh convergence. We opted for four values of the roundness tolerance of as many circumferences on both the part sides (Fig. 3). Using different mesh sizes, a variation in the temperature distributions occurs along the circumferences, which is in the order of a few degrees, which can significantly affect the part deformation. However, the charts in Fig. 4 show a growing trend of the roundness value in correspondence with each circumference. This trend settles down, generating insignificant differences between the results obtained with meshes 3 and 4. As the tolerance values are in line with those found by the quality control carried out on the moulded part, mesh 3 was chosen as discretization for the implementation of the next phase.

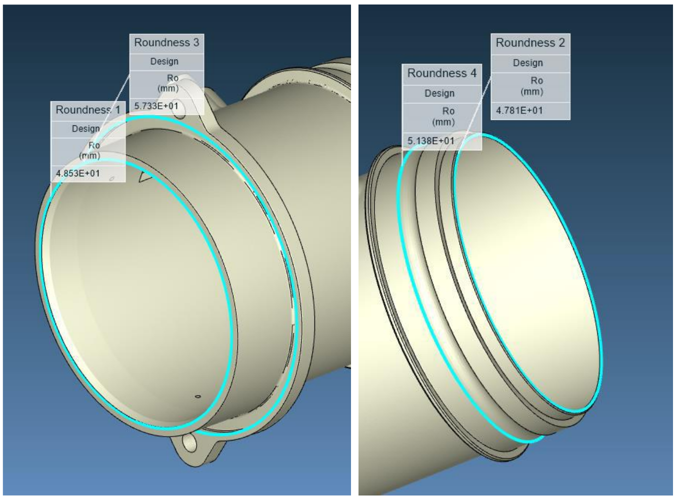

Fig. 3. Roundness tolerances for the comparison.

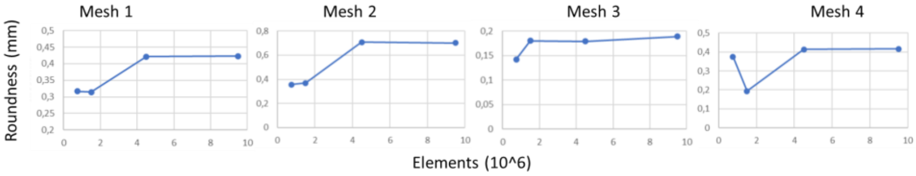

Fig. 4. Roundness trend in the 4 edges corresponding to different mesh sizes.

4.2 Simulation phase

In the second phase, we aim to simulate the behaviour of the injection moulded part as functions of the process parameters. In particular, a set of 16 (2^4) simulations, considering the injection velocity and the packing pressure parameters as inputs (Table 2), were carried out following a full factorial design. The outputs consist in the correlation between the two process parameters and the part deformation and shrinkage. In particular, we investigated a range of the packing pressure values that includes the value (85 MPa) normally used for the part production, by increasing and reducing its value (Table 2). This choice was made to evaluate the effectiveness with which the volumetric shrinkage of the material can be influenced, by varying the contribution of the compensating material during the packing phase, to ensure a lower distortion of the final geometry compared to that of the cavity. In fact, the shrinkage is one of the main causes of the part deformation in the side opposite the flange.

Conversely, as regards the injection velocity, it could be increased from the initial value of 80 mm/s, since the sprue pressure graph shows that the injection pressure limit is never reached during the injection phase.

Table 2. Factors and levels of the full factorial design (DOE).

Factors	Level 1	Level 2	Level 3	Level 4
Injection velocity (mm/s)	100	120	140	160
Packing pressure (MPa)	42.5	63.75	106.25	127.5

A four-level analysis was then carried out for the two parameters, using the uniform volumetric shrinkage (calculated according to the thermal effects at each point of the discretization) and the warpage as the parameters (responses) for evaluating the quality of the results. The software then carried out sixteen ~~simulations~~runs, representative of all the possible combinations of the selected parameters.

The curves in Fig. 5 link each parameter with the volumetric shrinkage. There is no shrinkage variation due to the injection velocity variation, while the packing pressure has a much greater effect on it, showing an important reduction of volumetric shrinkage at the maximum level of the packing pressure (127.5 MPa, i.e. the 72.8% of the maximum packing pressure of the injection machine in the real process).

As regard the injection velocity, the slight negative effect on the shrinkage conditions as the velocity increases is due to the increase in viscous effects at the gates, leading to a higher temperature of the molten material at the end of filling with respect to the standard process. Furthermore, there is also an increase in the maximum values of the viscous stresses, a logical consequence of the increase in velocity, which negatively affects the uniform shrinkage, therefore it is convenient to keep it at the standard (initial) level.

As regard the part deformation (warpage), the results show a substantial improvement of the geometric conditions of the part at the side opposite the flange, with a significant reduction of the displacements during the cooling phase (Fig. 6, left). This is due to the better compensation of the shrinkage of the region below the sensor housing. Fig. 6 (left) shows the results with the maximum value of the packing pressure (127.5 MPa), while Fig. 6 (right) shows the initial process. The improvement in terms of roundness (but also of dimensional tolerances) on the most critical circular edges (among those subjected to a specific design tolerance) is relevant. Conversely, there is an increasing deformation (displacements) in the flange region, due to the overpacking phenomenon, shown by the yellow areas in Fig. 6, left, which worsen the flatness condition that is obtained with the initial process parameters. However, the resulting values in the flange region are acceptable, so the value of the packing pressure generates the best uniform shrinkage, since there is an improvement in the deformation in areas subjected to tolerance, while the deterioration is localized in less important areas. This result was validated thanks to experiments on the real mould and the IM machine.

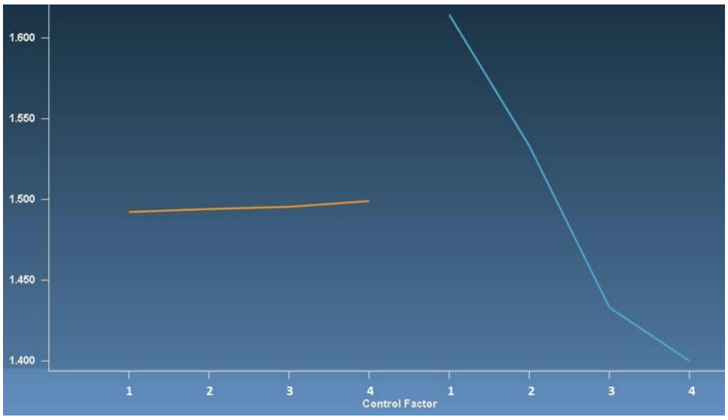

Fig. 5. The correlation between the volumetric shrinkage and the two control factors: (left) injection velocity and (right) packing pressure.

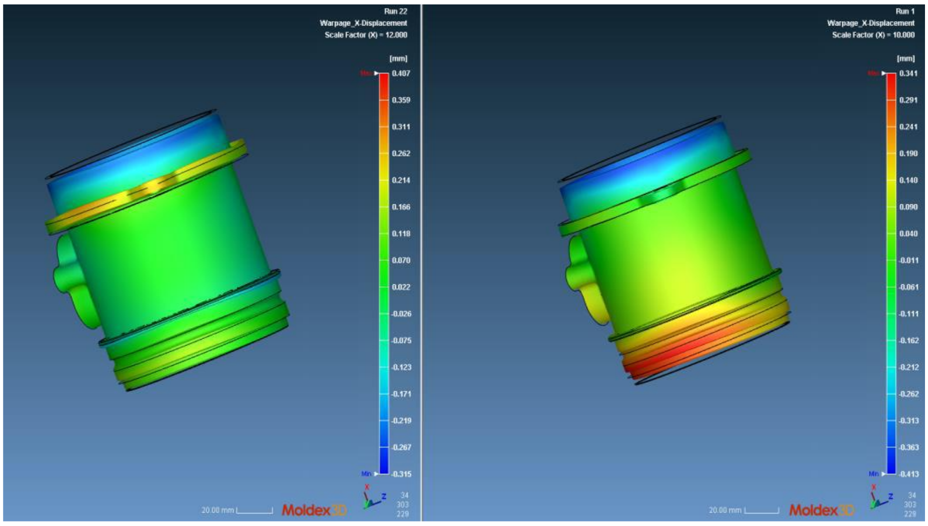

Fig. 6. Displacements along the axis of the component, using (left) the highest value of packing pressure (127.5 MPa); (right) the initial value of packing pressure.

Additional simulations were carried out to evaluate if a further increasing of the packing pressure may have positively affected the general deformation. The injection velocity was fixed at its initial value, and we ran three additional simulations in which the packing pressure increased (143.5 MPa, 159 MPa and 175 MPa, which corresponds to the maximum pressure limit allowed by the IM machine). However, due to bad results in the flange zone, and the risk of damages to the mould and the IM machine, these last three simulations were not validated with the real process.

5. Discussion and Conclusions

This work presents a study on injection moulded components to investigate the influence that the variation of the process parameters has on the part deformation, and therefore to predict and reduce the warpage, with particular respect to the functional features.

The study is based on two main design phases: Firstly, we develop a model of the mould system (cavity, runner, cooling system, mould, etc.) that can be reliable in the following simulation phase, and so capable of simulating the real behaviour of the system, thanks to the experimental validation with real data. This fine-tuning of the model considered the defeaturing of the part (removing unnecessary details), the modelling strategies of the mould elements, the mesh size and density. The analysis of the cooling efficiency reveals that the central baffle has the most important role in cooling the molten material inside of the cavity. Four different configurations of mesh elements in the cooling systems were investigated, but no advantages was found when using an increased number of elements with respect to what suggested by the CAE software. Finally, thanks to a convergence evaluation, the best number of mesh elements of the mould elements was determined and the resulting model was evaluated thanks to experimental data.

Secondly, to systematically assess the influence of the process parameters on the part deformation, we carried out a DOE factorial plan considering two process parameters as factors. The variation of the injection velocity (in particular its increase) did not return significant results, both from the point of view of shrinkage and deformation. To obtain positive results by acting on this parameter, changes to the mould would be necessary, designed to mitigate the increase in viscous effects. On the other hand, the packing pressure proved to be very effective in reducing the effects of volumetric shrinkage linked to thermal effects. In particular, by increasing the pressure up to about 72.8% of the maximum pressure limit allowed by the injection machine (127.5 MPa), a worsening of the overall deformation of the product was found, but a significant improvement in compliance with the tolerances of all the functional elements. In particular, in all areas subject to design tolerances, the range of the measured tolerance field is reduced compared to the initial process. The worsening of the deformation is concentrated in less relevant areas from the dimensional point of view, such as the flange. Therefore, although the software points out that there was an overall worsening of the part deformation, it also showed an improvement in tolerances in all the functional features.

Then, the simulations were carried out by returning to the injection velocity value used during the initial process, thus focusing only on the variation in the packing pressure. The model results reliable to predict the volumetric shrinkage and the warpage as revealed by the comparison with experimental data. The part obtained with the modified value of packing pressure already complies with the tolerances when it is extracted from the mould.

The described workflow is fully applied to a case study but can be easily generalized to other injection moulding components to predict and analyse their warpage and tolerances following the general two-phase procedure described in the Method section.

Some limitations of the current study are listed below. Firstly, the geometry of the mould system and the part were considered as inputs; therefore, we achieved an improvement of the existing production process acting only on the process parameters. Variations of the design parameters, such as the section of the gates, which could have influence on the results, were not considered.

Secondly, the cooling system geometry has not been changed, even if differentiating the flow rates of the cooling system on the two sides of the mould could ensure higher temperatures of the material in the area diametrically opposite to the sensor housing at the beginning of the cooling phase. This could lead to a lower differential shrinkage between the two sides of the component. In fact, the increase in the packing pressure has proved to be effective for reducing deformation, but it cannot be brought above certain values without worsening the elements that are not subject to problems related to shrinkage.

Thirdly, a further increase in the packing pressure, from the largest value used in the DOE calculations up to the maximum pressure limit, showed no significant benefits in terms of improvement of the results. The improvement of the volumetric shrinkage continues to be present but the effects of the overpacking become so significant in the flange area as to increase the width of the tolerance range of the circular features, worsening the overall quality. Furthermore, the resistance of the mould could set an insurmountable limit to the investigation of the highest values of packing pressure. For this reason, no experimental validation of these highest values was carried out.

Finally, the use of a smaller increment step of the packing pressure could have given better overall results (average between the condition that showed the best uniform shrinkage and the one that led to the best uniform deformation). It would therefore be possible to deepen the study by looking for an optimum condition for both these two parameters.

Acknowledgment. The authors acknowledge Cattini srl, San Martino in Rio (RE), Italy, and Moldex3D Italia srl, Lecco, Italy, for their valuable support.

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