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A method to predict early-ejected plastic part air-cooling behavior towards quality mold design and less molding cycle time

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A B S T R A C T

It is a common industrial practice to eject injection-molded plastic parts early, at a high temperature, and allow the parts to cool down in the air. This practice shortens the cycle time and reduces production cost. However, current commercial injection molding simulation software tools can only consider the in-mold cooling process. The simulation of the air-cooling stage after ejection is not well supported in such tools even though the air-cooling shrinkage is significant when plastic parts are ejected at high temperatures. The authors propose a Moldflow™-Ansys™ integrated FEA method to simulate the air-cooling process so that the air-cooling shrinkage can be considered at the early design stage and the quality of the part can be ensured with less molding cycle time. A real industrial case study is provided to show the procedure and its validation. The proposed method integrates Moldflow™ and Ansys™ by feeding Moldflow™ simulation results as the intermediate state data set into Ansys™ for air-cooling effect simulation. With a real testing product part ejected at a high temperature, the proposed approach shows promising predictions of the 3D warpage displacement. In this way, the cost factor of molding cycle time can be considered at the mold design stage and a cost-effective design can be developed.

1. Introduction

Current computer technology makes it possible to simulate the injection molding behavior [1–3]. The available commercial CAE simulation packages such as Moldflow™ and Moldex3D™ can accurately simulate the injection molding process at different molding stages so that engineers can understand how the plastic melt flows into the mold and evaluate the product warpage effect. If the parts do not meet their quality requirements, potential reasons can be identified and the mold design can be updated on computers until high quality plastic parts can be manufactured. A substantial portion of the product's final cost is determined at the early design stage [4,5]. Therefore, the accuracy of the CAE simulation is vital for the mold design in terms of the product quality and the final cost.

However, the available technology still has some limitations as the real injection molding production process is very complicated and hard to control precisely. It has been the claim of Moldflow™ that product deformation due to the injection molding process can be simulated. However, the detailed review can tell that the effective deformation during and after ejection was basically ignored. The commercial simulation packages can only consider the complex physical transition processes that happen in the mold. The calculation terminates at the end of the cooling stage. Therefore, the deflection result generated by the commercial simulation packages is only resulting from the residual stress accumulated during the in-molding stage. However, injection-molded plastic parts may continue to go through complex physical transitions during and after the ejection process. Both the ejection process and the transition after ejection will influence the final quality of the molded parts and neither processes are considered by the commercial software. The influence is significant and cannot be ignored, especially for plastic parts ejected at high temperatures. Therefore, the final shrinkage rates and product dimensions are inaccurate for such parts. So far, the authors have not found any effective tool that can readily predict the final product dimensions accounting for ejection deformation and air-cooling shrinkage and produce decent shrinkage and deformation distribution results when the product is ejected at a high temperature. Therefore, even with the help of these advanced tools, molding quality problems and optimizing the molding process remain complicated. Because early ejection is a problematic practice, companies tend to use more than the required time to ensure full solidification of the part before ejection.

The injection molding process is typically divided into 4 stages: filling, packing, cooling, and ejection [6–8]. Among these, the cooling stage takes the longest time and accounts for around 80% of the injection molding cycle [9–11]. At the same time, the majority of the shrinkage happens in the cooling stage, which will influence the

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product quality eventually. Poor cooling system design will result in longer cooling times, and will undermine productivity and increase production cost. What's more, in many cases product quality and the productivity are in conflict and cannot be optimized simultaneously [12].

The most widely used methods to improve cooling efficiency and shorten the injection molding cycle are to use cold water and increase the cooling water velocity. However, this may aggravate the pump burden and make the molding system more complicated. Ideally, the plastic parts should be fully cooled before ejection. However, waiting to eject the product, negatively influences productivity. The commonly used ejection criterion is that the whole part should be cooled down to the ejection temperature. However, this does not always happen. At the same time, it is not necessary for the product to be fully cooled to the ejection temperature before ejection. It is possible that the outer surface of the part may already be solidified and rigid enough to withstand the ejection force, but the interior part of the product may still be soft and in a transition state from molten to solidification with a temperature gradient. When the solidification layer is thick enough to stand the ejection force, and no plastic deformation will happen during the ejection process, the product can be ejected out at a relatively high temperature, in order to shorten the cycle time and improve productivity. When the plastic part is ejected from the mold, it does not factor into the cycle time anymore. This is a more favorable option than improving the cooling efficiency because no other device or subsystem is needed and it costs nothing. A shorter cycle time means lower production costs, increasing the company's competitiveness in the market.

In fact, it has been a common industrial practice to eject plastic parts before they have fully cooled to shorten the cycle time and save cost. For products with thick walls, especially, the center of the product is extremely hard to cool efficiently because plastic is such a poor conductor of heat. When the part's surface has already been cooled to a relatively low temperature, the temperature gradient between the mold and the product will be low. In this case, not too much heat can effectively be carried away by coolant, and increasing cooling times is not a favorable option. If such parts were to be cooled down to the ejection temperature, productivity would be too low

At the end of the in-mold cooling stage, the molded part is usually still very warm and the quantity of molten plastic remains significant, especially for thick wall product ejected early. After ejection, these materials will continue to cool to room temperature in air, with inevitable shrinkage. Certain plastic parts may have unevenly distributed wall thicknesses and mechanical properties so that the air-cooling process might cause complex, uneven deformations, which will account for a large portion of the whole product deformation.

However, to the authors' knowledge, so far, there have been no published, scientific reports on the study of early ejection and the possible problems involved. This paper aims to investigate the complexity of predicting the air-cooling shrinkage so that the injection-molded plastic parts can be ejected earlier, while maintaining product quality with a shorter cycle time. Then, the initial product CAD model and the mold design can be updated, based on the trustworthy simulation result, so that the air-cooling shrinkage can be considered at the early design stage and the quality of the part can be ensured with less cycle time. In this way, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved. Questions such as how to determine the ejection time and simulate the possible early ejection deformation by accurately predicting the transitional cooled part mechanical strength will be discussed in the second part of this series.

2. Literature review

Because the cooling stage takes the longest time during the injection molding process, many researchers have attempted to shorten the injection molding cycle time by optimizing the cooling system design to improve cooling efficiency [9]. Poor cooling system design results in longer cooling times and unevenly distributed temperatures, undermining product quality and productivity. Agazzi et al. [12] used the conjugate gradient algorithm and Lagrangian technique to optimize the cooling system design. They claimed that, by using this approach, a good compromise between productivity and product quality can be achieved. Wang et al. [13] proposed a Rapid Heat Cycle Molding process (RHCM) to produce a thin-walled plastic part. The mold is rapidly heated by steam to a temperature higher than the material glass transition temperature (Tg) and kept at the high temperature during the filling stage to ensure good plastic melt fluidity. Once the cavity is completely filled, cooling water will flow into the mold to cool the product quickly. In this way, high productivity and product quality can be produced. The author claimed that the total cooling time can be reduced by 15% with the RHCM process.

Nowadays, advanced manufacturing technologies provide engineers more options when designing the cooling channels. For example, 3D printing technology makes it possible to build conformal cooling channels which follow the shape of the mold surface and keep a uniform distance between the cooling channels and the mold surface around the product [14–16]. In this way, a more evenly distributed temperature and more uniform cooling effect can be achieved. Shayfull et al. [17] compared the cooling efficiency of conformal cooling channels and the traditional cooling channels over a front panel housing plastic part. They found that, by using milled groove square shape conformal cooling channels, the cooling time shortened more than 8% and a more uniform temperature distribution was achieved.

Some researchers are trying to integrate Moldflow™ and Ansys™ to obtain a more accurate picture of the injection-molded plastic product's mechanical performance, especially for products manufactured with fiber-reinforced plastic materials [18–20]. Kulkarni et al. [18] proposed a Moldflow™-Ansys™ integrated method to facilitate the design of a fiber-reinforced plastic injection-molded product by using Autodesk Moldflow™ Structural Alliance (AMSA). The fiber orientation of the product is predicted using Moldflow™ and then the anisotropy material properties are passed to Ansys™ using AMSA. Product structural analysis is carried out with Ansys™. They found that, compared to the isotropy material model, the orthotropic material model is more suitable for products manufactured with fiber-reinforced plastic material and the accuracy is more than 92%.

Current research, such as the RHCM technology [13] and the conformal cooling channels [17] mentioned above, focuses on improving the cooling efficiency to shorten the cycle time. These available technologies are all very useful in terms of shortening the cooling time. However, special devices or advanced manufacturing technologies are needed, which will make the molding system complex and costly. Early ejection is another possible way to shorten the cycle time. The proposed research work focuses on the natural plastic part shrinkage deformation during the air-cooling process. More specifically, the proposed research theoretically considers the air-cooling effect quantitively by accurately predicting the shrinkage that occurs during the air-cooling process so that it can be considered at the early design stage and the quality of the part can be ensured with less cycle time. In this way, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved.

3. Methodology

Usually, the initial plastic part CAD model is provided by the customers to meet their specific requirements, such as dimensions. Then the CAE simulation is carried out to investigate how the manufacturing process will influence the part dimensions and identify shrinkage rates. After that, design updates are carried out by incorporating the manufacturing-induced shrinkage rates to the initial part design, so that the updated design will satisfy the dimension requirements after going through the injection molding process. Usually, shrinkage rates induced

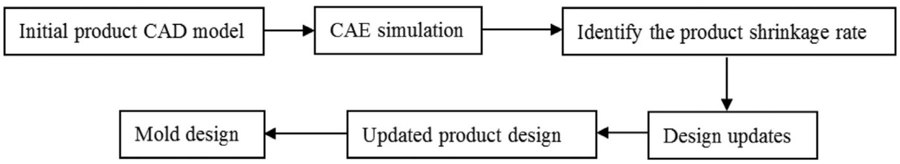

Fig. 1. Mold design workflow.

by the injection molding process are small and the shrinkage pattern for the updated design is similar to the initial product design. Therefore, another round of CAE validation simulation is not necessary in most cases. Finally, the mold can be designed based on the updated product design. In this way, the possible manufacturing induced problems can be addressed in the design stage. The workflow is shown in Fig. 1.

For the molding behavior thermal analysis, the temperature can be divided into two parts: the fluctuating component and the cycle-average component. The fluctuating component is much smaller than the cycle-average component and can be ignored during the cooling simulation [17]. During the continuous injection-molding operations, the cycle-averaged temperature reaches a steady state. The heat balance during an injection molding cycle can be expressed as [17].

$$\sum^{Q} = Q_P + Q_C + Q_E = 0 \quad (1)$$

In which, Q_P – heat carried in by the molten plastic;

Q_C – heat carried out by coolant;
Q_E – heat dissipated to the surrounding environment.

The product will cool down during the cooling stage. The governing equation for the mold cycle-average temperature distribution can be expressed as [21]:

$$\kappa\left(\frac{\partial^2 \mathrm{T}}{\partial \mathrm{x}^2} + \frac{\partial^2 \mathrm{T}}{\partial \mathrm{y}^2} + \frac{\partial^2 \mathrm{T}}{\partial \mathrm{z}^2}\right) = 0 \quad (2)$$

When the hot melt is injected into the relatively cold mold, the part surface will solidify quickly due to the high thermal conductivity of the metal. However, the thermal conductivity of the plastic material is much lower. Therefore, the cooling effect is significantly influenced by the heat transfer rate within the plastic part from the inner region to the outer surface which can be expressed as [22]:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial s}\left(\kappa_p \frac{\partial T}{\partial s}\right) \quad (3)$$

In which, κ_p – thermal conductivity for the molten plastic;

s – direction along the part thickness.

The heat carried in by the molten plastic should be removed during the injection molding cycle so that the part can be cooled down to the recommended ejection temperature. The heat can be removed through 3 approaches: 1. Heat transfer between the mold surface and the product; 2. Removed by the coolant; 3. Thermal dissipation through the mold surface.

The heat flux $\bar{q}$ between the mold cavity surface and the molten plastic is given by the following equation [23]:

$$\bar{q} = -\kappa_m \frac{\partial T}{\partial \tilde{n}} \quad (4)$$

In which, κ_m – thermal conductivity between the mold cavity surface and the molten plastic;

$\tilde{n}$ – direction normal to the surface.

$$\bar{q} = \frac{1}{t_f + t_c + t_o}\left[\int_0^{t_f} q_1(t)dt + \int_{t_f}^{t_f+t_c} q_2(t)dt + \int_{t_f+t_c}^{t_f+t_c+t_o} q_3(t)dt\right] \quad (5)$$

In which, t_f, t_c, t_o – filling, cooling, and mold opening time respectively;

q_1, q_2, q_3 – instantaneous heat flux values during filling, cooling, and mold opening time respectively.

The heat removed by the coolant can be expressed as [24]:

$$\kappa_m \frac{\partial T}{\partial \tilde{n}} = h_c(T_w - T_c) \quad (6)$$

In which, h_c – heat transfer coefficient between the mold and the coolant;

T_w – mold temperature;
T_c – coolant temperature.

The heat dissipation through the mold surface to the ambient air can be expressed as [23]:

$$\kappa_m \frac{\partial T}{\partial \tilde{n}} = h_a(T_w - T_a) \quad (7)$$

In which, h_a – heat transfer coefficient between the mold and the ambient air;

T_a – temperature for ambient air.

Plastic material can be divided into semi-crystalline plastics and amorphous plastics based on whether crystallization occurs during the cooling process. Semi-crystalline plastics have an ordered pattern of molecular chain while the molecular chain for amorphous plastics is randomly distributed. The main reason for plastic product warpage is cooling shrinkage, which is inevitable because the plastic material's specific volume varies with temperature and pressure. The specific volume changes incorporate the crystallization phenomenon for semi-crystalline plastics during the molding process. The plastic material's specific volume change at different cooling rates follows a 2-domain Tait equation which is expressed as follows [25–28]:

$$v(T, p) = v_0(T)\left[1 - C\ln\left(1 + \frac{p}{B(T)}\right)\right] + v_t(T, p) \quad (8)$$

in which, $v(T, p)$ – specific volume at given temperature (T) and pressure (p);

$v_0(T)$ – specific volume when the pressure is 0;
C – a constant equal to 0.894; and
$B(T)$ – the pressure sensitivity for the material related to temperature (T).

Generally speaking, the plastic material's specific volume goes up when the temperature increases and goes down when the pressure increases. The plastic part morphological phases changes with the temperature during the injection molding process: from melted state at a high temperature level, to semi-solid when the coolant flows into the mold and the temperature drops, and finally to solid state when the product is fully solidified at low temperature level. The change of the plastic material's specific volume during the injection molding process

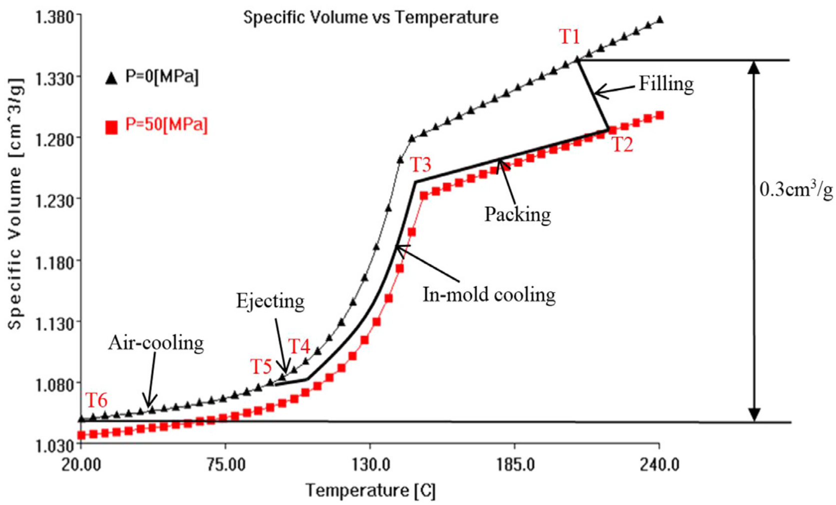

Fig. 2. Specific volume curve of typical HDPE [29].

is usually illustrated with PVT (Pressure – Volume - Temperature) curves. Fig. 2 gives the PVT curves of HDPE covers a wide temperature range from 20 °C to 210 °C, during which the plastic material goes through different morphological phases: melted, semi-solid, solid, etc. While the solid black curve in Fig. 2 highlights an example of molding part's shrinkage characteristics. T1–T2 represents the filling stage, T2–T3 represents the packing stage, T3–T4 represents the in-mold cooling stage, T4–T5 represents the ejection stage, T5–T6 represents the air-cooling stage. It is developed with reference to Moldflow™ material library [29].

The molded part's thermal-mechanical process history and the mold constraints determine the product's warpage behavior. Plastic part deformation is caused by material shrinkage during the molding process and it is influenced by many factors such as part design, mold design, molding process parameters, material properties, etc. Fig. 3 shows the injection-molded part's temperature history. During the filling stage (T1—T2 shown in Figs. 2 and 3), the plastic melt is injected into the mold at a high temperature to ensure high fluidity so that it can fill the mold easily. The pressure at the mold gates increases gradually to overcome the flow resistance and the temperature increases from melt temperature T1 to T2 during the filling process. Refer to Figs. 2 and 3, assume the melt temperature is set to 210 °C and the packing pressure is 50 MPa, which are the same as the recommended process settings for a generic HDPE [29]. When most of the cavity is filled, the molding machine will maintain high pressure for a short period of time, around 15% of the total cycle time, known as the packing stage (T2—T3). During the packing stage, the pressure remains almost the same but the temperature decreases gradually to T3, to ensure the gate is fully solidified at the end of the packing. Then, the coolant removes most of the heat during the in-mold cooling stage (T3—T4). At the same time, the molded part begins to solidify and both the temperature and pressure decreased until ejection. After that, the part is ejected from the mold. During the ejection process, the part will cool down a little bit to T5 and the pressure is released. Immediately after the part is ejected from the mold, there are no more mold constraints and the part will shrink freely until it reaches room temperature, T6. Note that the period from T5 to T6 is the so-called *air-cooling* period.

The shrinkage during in the mold with mold constraints and out of the mold in the open air are entirely different processes. The theoretical specific volume change of an HDPE during the injection molding process is shown in Fig. 2, i.e. approximately 0.3 cm^3/g. However, during the in-mold cooling stage, the mold configuration will constrain the part from shrinking freely and the part tends to copy the mold geometry. The mold also shrinks during this process to cancel the thermal expansion that happened during the injection molding process, which is less than the plastic part. Therefore, the strain is created within the plastic part and the residual stress accumulates in the molded part.

After being ejected out from the mold, there is no more mold

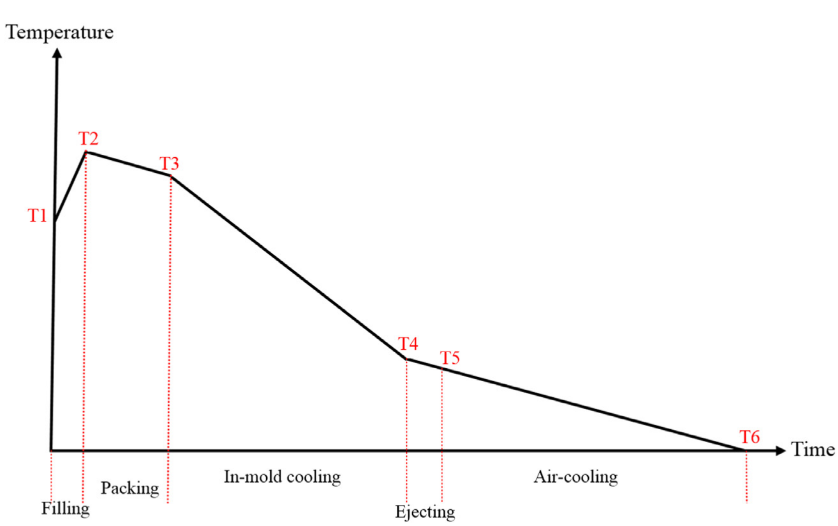

Fig. 3. Injection molding product average temperature history.

constraint and the part will continue to shrink freely in the open air. During the air-cooling process, the unevenly distributed residual stress accumulated during the in-mold cooling process will be released. The residual stress release and the shrinkage during the air-cooling process will make the product deviate from the cavity shape and produce the final shape of the plastic product with the unwanted warpage. The shrinkage rate will be different for the plastic part cools in the mold with mold constraints and the same product cools freely in the open air with no constraints. However, commercial injection molding simulation packages can only consider the in-mold cooling process which is forced by coolant with mold restrictions. The air-cooling shrinkage out of the mold is omitted.

The heat of the molten plastic should be removed by the coolant so that the part can be cooled to the ejection temperature. The ejection temperature is recommended by material suppliers, which is based on American Society for Testing and Materials (ASTM) D3418 standard test method [13,29,30]. Based on the heat balance, for amorphous polymers, the in-mold cooling time can be estimated as follows [17,31,32]:

$$t_c = \frac{s^2}{\pi^2\alpha}\ln\left[\frac{4}{\pi}\left(\frac{T_M - T_W}{T_E - T_W}\right)\right], \tag{9}$$

in which, t_c is the required cooling time;

s is the part thickness;
α is the effective thermal diffusivity;
T_M is the melt temperature;
T_E is the average ejection temperature;
T_W is the mold cavity surface temperature.

For semi-crystalline polymers, the solidification time can be can be estimated as follows [33]:

$$t_s = \frac{1}{\alpha}\,\frac{\left(\frac{s}{2}\right)^{2}}{2\beta c} \tag{10}$$

in which, t_s is the required solidification time;

β is the root of transcendental equation;
c is the parametric constant.

As mentioned previously, Moldflow™ can simulate well the injection molding process that happens in the mold. However, it can not support the air-cooling process simulation. Ansys™ has both the thermal and structural analysis modules which can predict the thermal residual stress and so also the structural response. Ideally, the integration of Moldflow™ and Ansys™ can combine the advantages of each software and predict the final product dimensions more accurately with both the in-mold cooling and the air-cooling shrinkage considered.

The integration of Moldflow™ and Ansys™ is not an easy task as Moldflow™ is not an open sourced software. Further, both Moldflow™ and Ansys™ run in their own environment. One common problem for the integration of different softwares is that some information may get lost during the integration. In order to integrate Moldflow™ and Ansys™, both geometrical information, non-geometrical information and the simulation results should flow from Moldflow™ into Ansys™. The integration between Moldflow™ and Ansys™ can be achieved in many ways: Neutral Data File (NDF), Moldflow™ Structure Alliance and Moldflow™-Ansys™ Application Programming Interface (API). IGES and STEP are NDFs widely used to transfer data from one domain to another. Moldflow™ has an API (mpi2ans.vbs) that enables the transfer of both geometrical and non-geometrical data into Ansys™. Moldflow™ Structure Alliance was developed by Moldflow™ to enable the interoperability between Moldflow™ and Ansys™.

In this paper, Moldflow™-Ansys™ API has been used to achieve the integration. The integration semantic model is shown in Fig. 4. The initial 3D product model is first simplified in the CAD system and then imported into Moldflow™. In Moldflow™, cooling channels and feeding systems are created and process parameters and material data are specified. Then, the injection molding simulation is carried out and the simulation result obtained. After that, Moldflow™-Ansys™ API is executed and generates the integration files which contain both the geometrical information and the non-geometrical information. Together with the temperature distribution results from Moldflow™, the Ansys™ simulation is carried out and the final product shrinkage rates after the part cools down to the room temperature are obtained. Then design updates are carried out by incorporating the manufacture-induced shrinkage to the initial product design, so that the updated design will satisfy the dimension requirements after going through the entire injection molding process. Finally, the mold can be designed accordingly.

The Moldflow™-Ansys™ Application Programming Interface (mpi2ans.vbs) can generate two interface files: the Moldflow™-Ansys™ intermediate file (.cdb); and the initial residual stress file (.ist). The Moldflow™-Ansys™ intermediate file contains the mesh information, material properties, node number, node location, constraint, and coordinate system. The initial residual stress file contains the Moldflow™ simulated residual stress accumulated during the injection molding process from T1 to T4 for all the element, but does not include the thermal residual stress generated during the air-cooling process (T4–T6). Therefore, the product temperature distribution at the end of the in-mold cooling process (T4) is also needed, as the initial condition to do the air-cooling simulation. Moldflow™ calculates the temperature distribution at each node and then forms the result for the whole product. The temperature distribution result at the end of the in-mold cooling process, together with the corresponding node number, can be exported as Patran format. At this point, all the information needed to do the air-cooling simulation is available. An Ansys™ *vread* command is used to read in the temperature distribution result and the corresponding node number as two arrays, and then to apply the temperature to each node as the thermal load. Together with the initial residual stress result and the material properties provided by Moldflow™ material library, the Ansys™ simulation is ready to go. Finally, we can get a more accurate simulation result that considers the whole injection molding process. In this way, the air-cooling shrinkage can be considered at the early design stage and the quality of the part can be assured with less cycle time by ejecting the part earlier. Therefore, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved.

4. Case study

Tough grip is a product used in the oil industry to guide rods. It requires very precise dimensions so that it can fit a hole and a rod simultaneously. The product, produced by Drader Manufacturing Industries Ltd., has some quality problem. As shown in Fig. 5, the shrinkage rates for different sections are not the same and the final dimensions are hard to control. The shrinkage rate is defined as the relative dimension change caused by the injection molding process, as shown in Eq. (9). For the real products, the shrinkage rates change from 5% to 9% at various points around the product.

$$\text{shrinkage rate} = 1 - \frac{\text{real product dimensions}}{\text{product designed dimensions}} \tag{11}$$

First, all the small features are removed such as the characters on the surface and the edge blends at the holes. After that, the feeding system and the cooling systems are created according to the real mold design. Fig. 6 shows the meshed product with cooling channels and feeding system. The mesh size is 3 mm.

Real process parameters collected from our industry partner shown in Tab. 1 are fed into Moldflow™. There are four sets of cooling channels in the mold, and hot water (65.56 °C) is used as the coolant. The flow rates for the four sets of cooling channels are different and more details

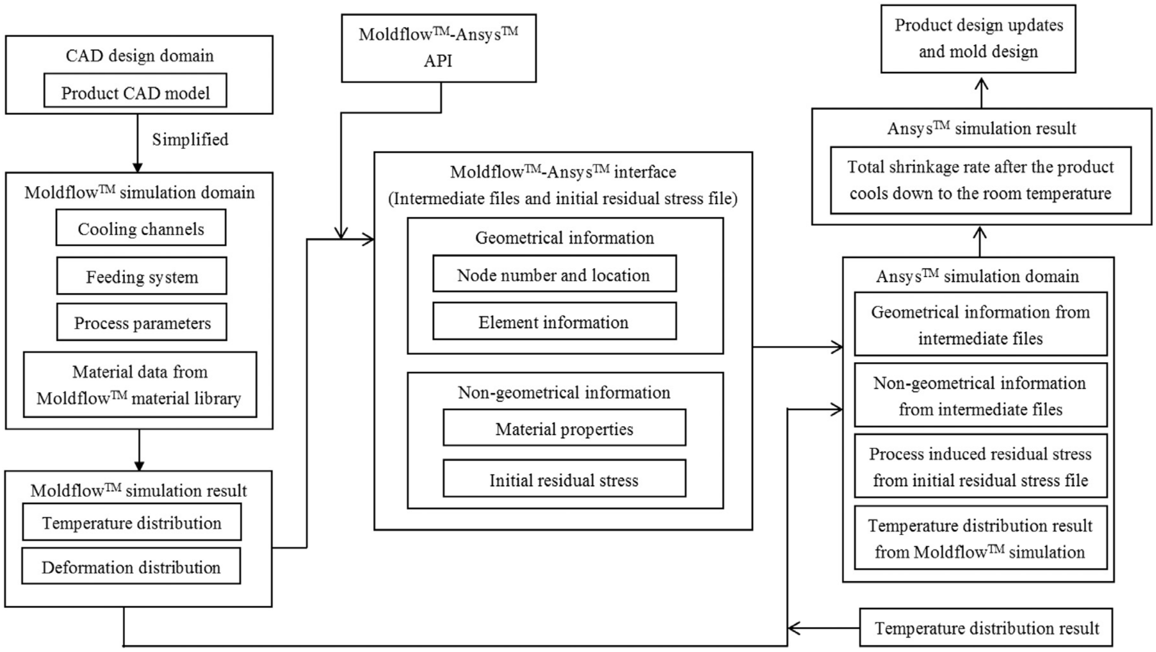

Fig. 4. Schematic of the proposed approach.

are shown in Tab. 2.

The material used in Drader to produce the tough grip is PA66 from ADELL PLASTICS, which is not in the Moldflow™ material library. Although the material supplier provides a test report about the material [34], it only has some basic material properties such as tensile strength, and elongation, which are insufficient for the simulation. Hence, a material type that behaves similarly, BASF Ultramid A3Z HP, is employed in this research to replace the original material [34,35]. The material properties for BASF Ultramid A3Z HP are shown in Table 3 [29,35].

The injection molding simulation was carried out with Moldflow™, using the real process settings shown in Table 1 and the deflection result is shown in Fig. 7. Based on Eq. (3), the shrinkage rates for both the top and the bottom sections are around 2.9%, the shrinkage rate for the upper slot is 4.54% and the shrinkage rate for the bottom slot is 4.2%. The exact shrinkage rate obtained from Moldflow™ simulation is shown in Table 4. It can be seen that the shrinkage rate obtained from Moldflow™ simulation differs significantly from the real product.

Fig. 8 shows the product temperature result. It can be seen that the product is very hot at the end of the in-mold cooling process. It is also interesting to notice that the holes are extremely hot as they are so narrow and no cooling lines can go into them.

As can be seen from Fig. 9, the product interior temperature is very high at the end of the in-mold cooling process, even higher than the Moldflow™ recommended ejection temperature which is 213 °C [29]. After a further scale down of the temperature result, it is worth noticing that more than 20% of the material is hotter than 213 °C at the end of the in-mold cooling process. As can be seen from Fig. 9, in the thickness direction, around half of the plastic material is hotter than the recommended ejection temperature and close to molten state, even after the in-mold cooling process. The authors suggest that the main reason for the difference in shrinkage rates between the Moldflow™ simulation

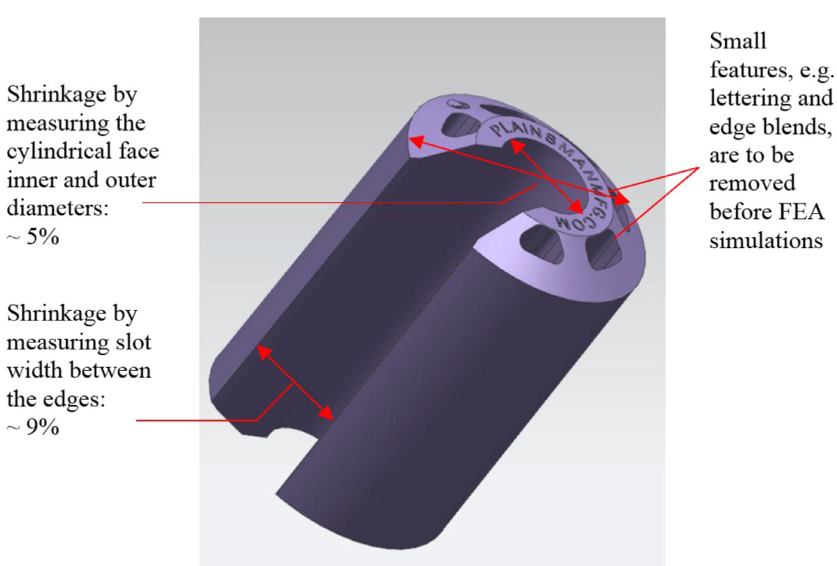

Fig. 5. Original 3D CAD model of the product.

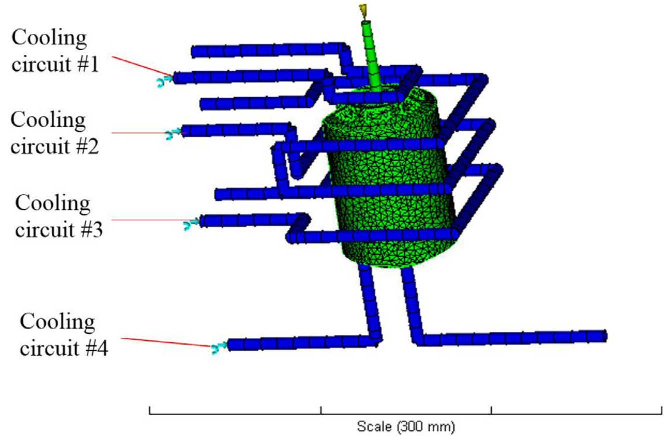

Fig. 6. Meshed product with cooling channels and feeding system.

Tab. 1
Moldflow™ process settings.

Melt temperature	274 °C	Cooling time	45.4 s
Injection time	1.6 s	Coolant	water
Packing time	8 s	Packing pressure	27.6 MPa

Tab. 2
Cooling channel flow rates provided by the industrial partner.

Flow rate	Cooling channel			
	Cooling channel #1	Cooling channel #2	Cooling channel #3	Cooling channel #4
Gallon per minute	1.7	2.3	2.0	2.8
Liter per minute	6.44	8.71	7.57	10.6

Tab. 3
Material properties of BASF Ultramid A3Z HP.

Elastic modulus (E1)	1920 MPa	Poisson's ratio	0.37
Elastic modulus (E2)	1880 MPa	Shear modulus	890 MPa
Coefficient of thermal expansion (α1)	0.0001181 1/°C	Coefficient of thermal expansion (α2)	0.000121 1/°C
Glass transition temperature (Tg)	75 °C	Melting temperature (Tm)	260 °C

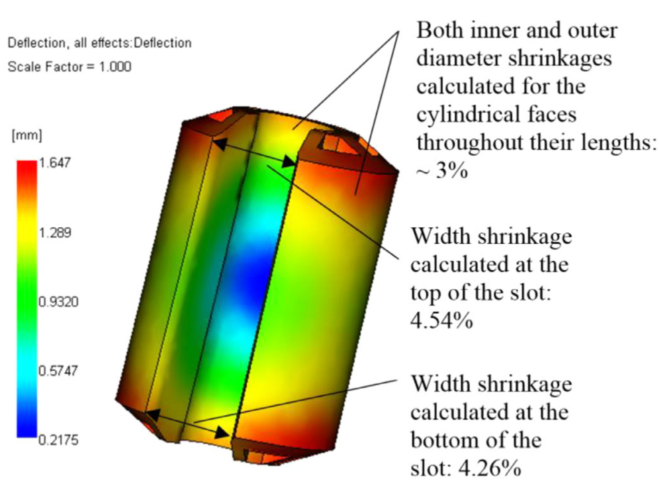

Fig. 7. Simulation result with real process settings.

Tab. 4
Shrinkage rate for Moldflow™ simulation.

	Upside width			Downside width		
	Outer diameter	Inner diameter	Edge distance	Outer diameter	Inner diameter	Edge distances
Before deformation(mm)	67.69	24.35	18.95	68.49	25.23	19.97
After deformation(mm)	65.8	23.62	18.09	66.55	24.55	19.12
Shrinkage (%)	2.79	3	4.54	2.83	2.7	4.26

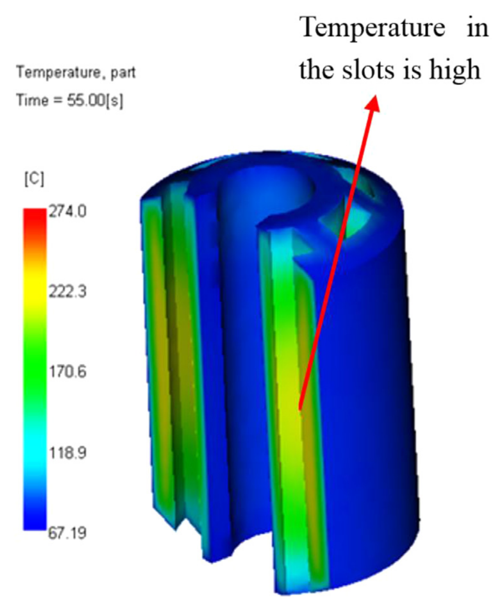

Fig. 8. Part temperature result.

and the real product is that Moldflow™ cannot simulate the air-cooling process so that the shrinkage during the air-cooling process is not considered. The product shrinkage rates which only considers in-mold cooling shrinkage are unavailable due to the part is extremely hot when been ejected, so it is unable to measure. More research is needed to simulate the whole cooling process which includes both the in-mold cooling process considered by Moldflow™ and the air-cooling process that has not been considered to date.

Using the method mentioned above, Moldflow™-Ansys™ Application Programming Interface (mpi2ans.vbs) is executed and generates two interface files: the Moldflow™-Ansys™ intermediate files (.cdb) and the initial residual stress file (.ist). Together with the temperature distribution result provided by Moldflow™, the Ansys™ simulation is ready to go and the simulation result is shown in Fig. 10. The Ansys™ simulation convergence criteria are force convergence with the convergence limit 0.005 and displacement convergence with the convergence limit 0.05.

Based on the node distance before and after the injection molding process, the shrinkage rates can be obtained using Eq. (3). The total shrinkage rates after the product cools to room temperature are shown in Table 5. Compared to the shrinkage rates obtained from Moldflow™, the Moldflow™-Ansys™ integrated simulation result is closer to the real product. Based on the total shrinkage rates, the initial product design can be updated and the mold can be designed accordingly, which considers the air-cooling shrinkage at the initial design stage so that the quality of the part can be assured with less cycle time. In this way, the cost factor can be considered at the mold design stage and a cost-effective injection mold can be designed.

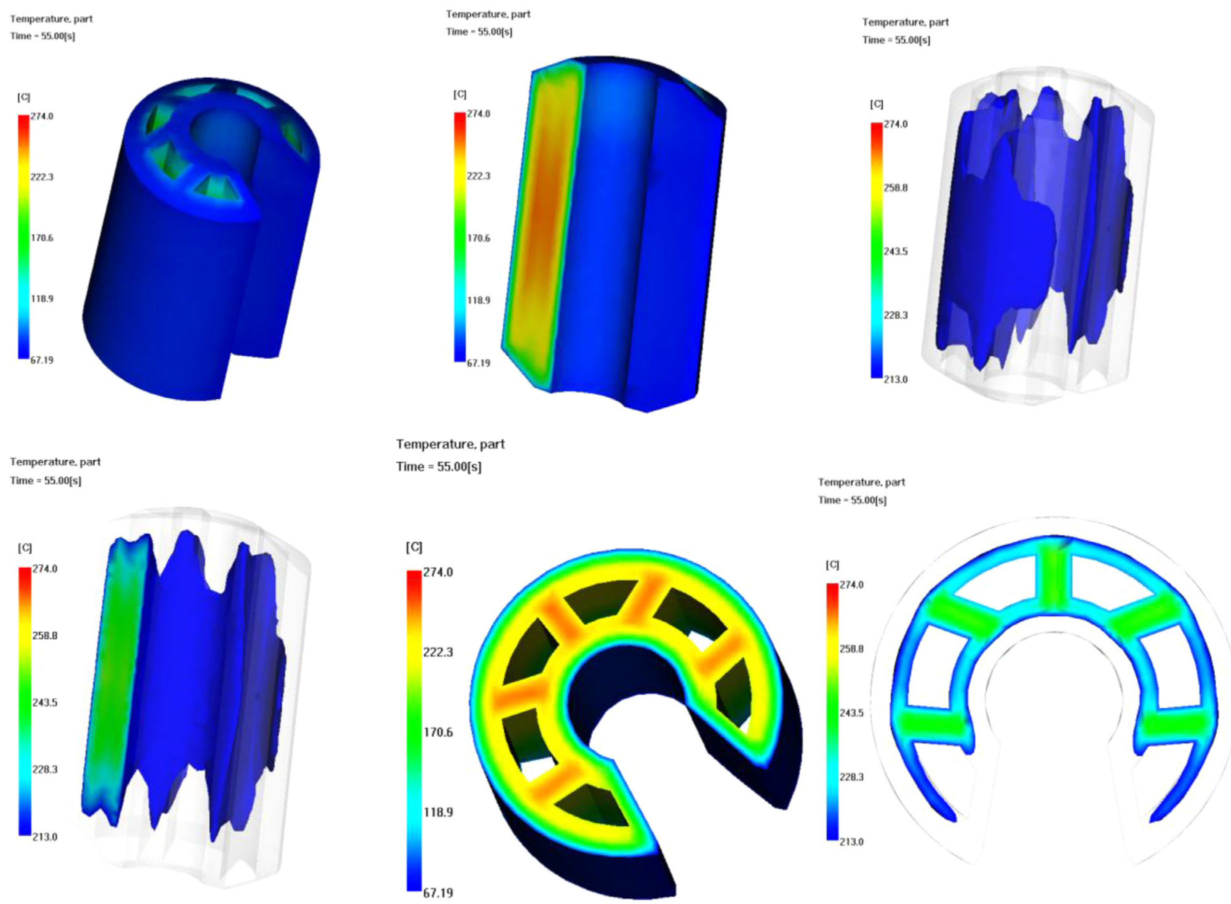

Fig. 9. Product interior temperature.

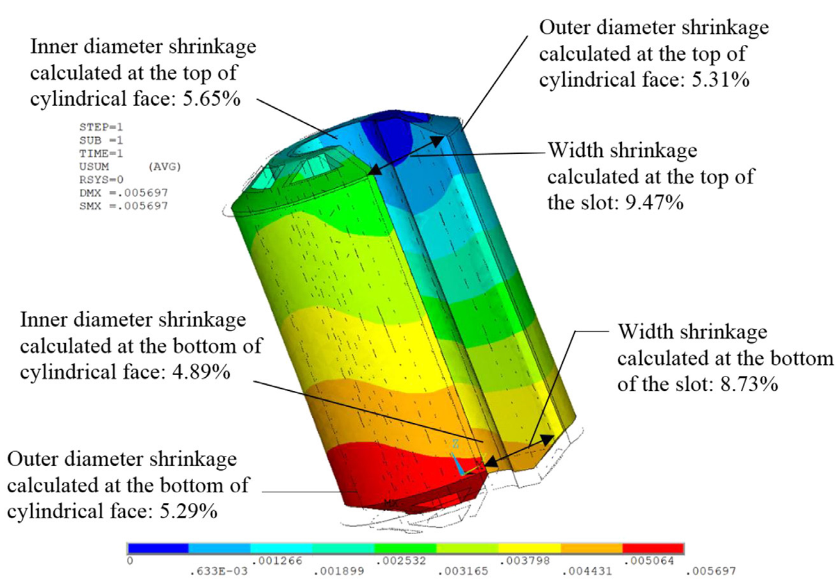

Fig. 10. Deformation after air-cooling process.

5. Conclusion and future work

Ejecting molded plastic parts at high temperatures is a common industrial practice to shorten the cycle time and improve productivity. However, when parts are ejected at high temperatures, the product dimensions and warpages are hard to predict and control. Commercial injection molding simulation tools can only simulate the injection molding process up to the end of the in-mold cooling stage and the air-cooling process is ignored. The authors proposed an integrated Moldflow™-Ansys™ simulation method to analyze the entire injection molding process up to the part being cooled to room temperature so that the air-cooling deformation effect can be evaluated at the early mold design stage, and the dimensional and geometrical quality of the part can be ensured with less cycle time. A real industrial case study has

Tab. 5
Simulation shrinkage rate with PA from Moldflow™ and then Ansys™.

	Upside width			Downside width		
	Outer diameter	Inner diameter	Edge distance	Outer diameter	Inner diameter	Edge distances
Before deformation(mm)	67.69	24.35	18.95	68.49	25.23	19.97
After deformation(mm)	64.097	22.975	17.156	64.867	23.997	18.227
Shrinkage (%)	5.308	5.645	9.469	5.290	4.886	8.730

been presented using the proposed approach, and the geometric measures obtained from the integrated simulation method show good alignment to the real production result, which is not achievable by using Moldflow™ simulation alone, especially for plastic parts ejected at a high temperature. In this way, the cost factor for molding production can be considered at the mold design stage and a shorter molding cycle time can be achieved due to well-optimized early ejection. The proposed method works for both the thin wall and thick wall plastic parts ejected at a high temperature.

This research assumes that the injection-molded plastic part has been cooled, within a mold, rigid enough to withstand the ejection force and no plastic deformation happens during the ejection process. Therefore, how to determine the ejection time so that the solidification layer is thick enough to withstand the ejection force and no excessive plastic deformation will occur during the ejection process must be investigated further. More challenging questions can be identified: (1) the extent and spatial pattern of the transitional plastic deformation during the ejection process; (2) how much ejection force can be used to ensure the part maintains its structural integrity; (3) how to optimize the part and mold designs with the insight of the predicted part dimensions and 3D deformations during the air-cooling. It is possible that, by revealing the complete deformation of the whole injection molding process at the design stage, plastic part quality can be better assured and molding cycle time optimized.

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Conflict of interest statement

Conflict of interest for all authors – None.

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