Title:
Mold Modification to Fix Warpage with Cooling Prediction for Plastic Products

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Introduction:
Warpage is a common quality problem for the injection molded products and it is extremely difficult to solve. Most cases can only be addressed with engineers' experience. Nowadays, the great advancement of the computer technology makes it possible to simulate the injection molding process with confidence. Such simulations can help us to understand why a warpage problem occurs and how to fix it. Compared to the traditional way, this work is regarding a cooling prediction approach with CAE technology that can greatly shorten the mold modification process and address warpage issues, even after the mold has been produced.

Literature review:
Most of researchers follow an ideal workflow to minimize the chances of warpage, i.e. starting from plastic part design, followed by molding process analysis to check and avoid process issues, like warpages, and then finalize the mold design. Oktem et al. [1] conducted a series of experiments to find the best combination of injection time, packing pressure, packing time and cooling time to manufacture a thin-shell plastic component using Taguchi method. They found that packing pressure is the most significant process parameter influencing the warpage of thin-shell plastic products. Yang et al. [2] compared the warpage effects of an original flat plastic part geometry and three other designs of different ribbed geometries via CAE analysis. They claimed that the warpage decreased significantly if both the geometry and parameters of the ribs are well selected. Agazzi et al. [3] used conjugate gradient algorithm and Lagrangian technique to optimize the cooling system design. The optimized cooling system results in evenly distributed temperature for mold areas surrounding the molding part, so the warpage reduced. Shayfull et al. [4] compared the cooling efficiency of conformal cooling channels and the traditional cooling channels over a front panel housing product. It is reported that the temperature distribution uniformity improved as much as 50% and the cooling time shortened more than 8% by using milled groove square shape conformal cooling channels.

However, in industrial practice, it is very common that the mold has already been manufactured and the production is running when the defects are discovered. This situation is usually caused by tight production schedules or the lack of engineering analysis capability in companies. Therefore, there is a need to investigate effective ways to solve the warpage problem at the late stage. In this paper, a new workflow is proposed and four methods suggested fixing the warpage problem when the mold has already been made.

The limitations of the traditional method to address warpage problems after the mold made:
The traditional way to solve warpage problem after mold made is largely based on the knowledge and experience of the engineers. In most cases, the engineers do not have a clear picture about the reasons resulting in warpage. The quality of the molded product could only be evaluated after the test shoot.

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The traditional warpage solving approach after mold made is no longer adapted to the modern market economy because a lot of time and money is investigated into the mold modification process.

<u>The proposed workflow to address warpage problems after the mold made:</u>

The mold modification process has been greatly shortened with the help of advanced computer-aided-engineering (CAE) software, which makes it possible to evaluate the quality of plastic product on computers. The proposed process to solve warpage problem after mold made has the following steps: (1) utilize the CAD model of the plastic product together with the detailed mold design model with the feeding system, cooling channels, and export the geometrical entities to molding simulation CAE software via Neutral Data File (NDF). This step realizes the transfer of geometrical information. (2) Setup CAE analysis conditions. After applying the non-geometrical information such as material properties, process parameters and etc. the simulation is ready to go. (3) Conduct molding process simulation with cooling effect analysis. Based on the simulation results, such as temperature distribution, we can identify the causes resulting in any warpage. (4) Modify the mold design or the process parameters to address the warpage issues accordingly. (5) Verify whether the mold modifications and the new process parameters can produce qualified products. (6) Iterate the mold design modification and analysis cycle. If the simulated product results meets the customer's requirement, we can begin to modify the real existing mold; if not, we should modify the mold design or change the process settings again on the computer and do another round simulation, until high quality product is produced. The proposed workflow to solve warpage problem after mold made is shown in Fig. 1.

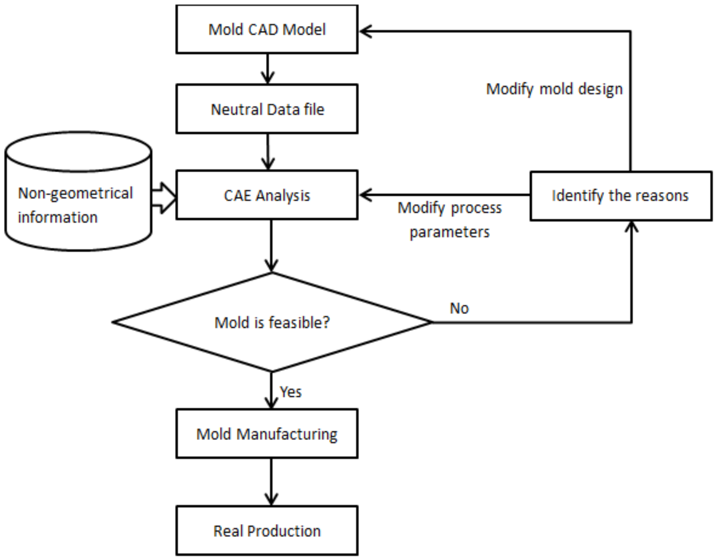

Fig. 1: Modern warpage resolve workflow after the mold made.

<u>Analysis of warpage influencing factors:</u>

The fundamental reason for warpage of the plastic product is shrinkage. It is inevitable because the specific volume of plastic material varies with temperature and pressure. The specific volume of plastic material follows 2-domain Tait equation which expressed as following [5]:

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

in which $v(T,p)$ is the specific volume at given temperature (T) and pressure (P); $v_0(T)$ is the specific volume curve when the pressure is 0; C is a constant equals to 0.894; B(T) is pressure sensitivity for the material related to temperature (T). Generally speaking, the specific volume of the material goes up when the temperature increase and goes down when the pressure increased. This characteristic of plastic material is illustrated in the PVT (Pressure – Volume - Temperature) curves. Fig. 2 shows the

PVT curve of generic shrinkage characterized HDPE [6], where the bold solid curve indicates the molding process stages.

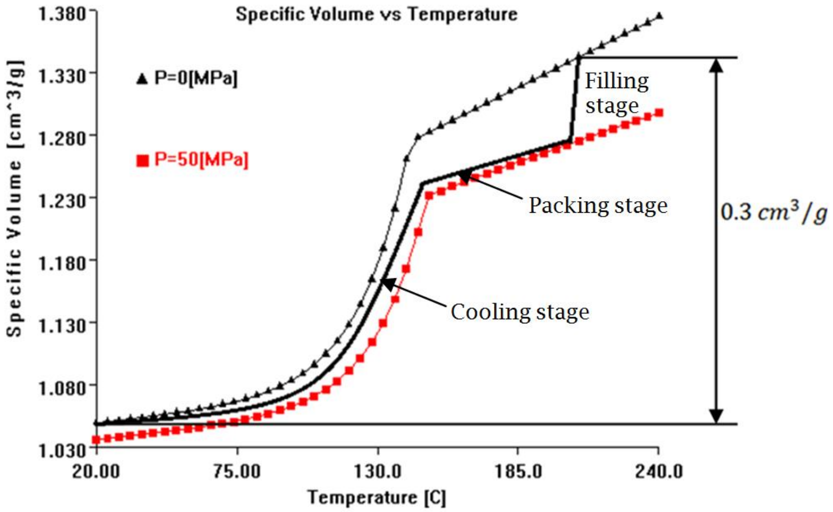

Fig. 2: PVT curve of generic shrinkage characterized HDPE [6].

The thermal-mechanical process history of the product and mold constrains result in the warpage of product. During the filling stage, the plastic melt is injected into the mold at a high temperature to ensure high fluidity so that the mold can be filled easily. The pressure at the gates of the mold increases gradually to overcome the flow resistance in cavities during filling stage, and then maintains a high level in the packing stage. According to Fig. 2 and recommended process settings, let us assume the melt temperature is 210 ℃ and the packing pressure is 50 MPa for generic HDPE [6]. When most of the cavity is filled, the packing stage begins. During packing, the pressure is remained almost the same but the temperature decreases gradually to ensure the gate solidified at the end of the packing stage. Then, coolant flows in the cooling system and removes most of the heat during the cooling stage. At the same time, the molded product begins to solidify and both the temperature and pressure decreased until ejection. After ejected out from the mold, the product continues to cools down till the room temperature. As can be seen in Fig. 2, the specific volume of generic HDPE decreased approximately $0.3\ cm^3/g$ during the injection molding process, but the plastic product could not shrink freely because of the mold constrains. The mold also shrinks during the cooling process to cancel the thermal expansion during injection molding process. However, the metal mold shrinks much less than the plastic product. Therefore, the strain in the plastic part is created and the residual stress accumulated into the molded product. After being ejected out from the mold, there is no more mold constrains and hence the unevenly distributed residual stress will release and make the product deviate from the cavity shape and produce the final shape of the plastic product and so is the unwanted warpage. Clearly, minimizing the warpage of the product should be considered during both the product design and mold design stages.

Proposed method to minimize warpage after mold made:

There are four promising options in this situation to fix the warpage issue: (1) modifying the cooling channels; (2) changing plastic material; (3) optimizing the process parameters; and (4) using mold inserts. In this paper, the authors investigated the mechanisms and effectiveness of these four options, and developed a simulation-guided interactive method to fix a warpage problem with quantitative and predictive measures.

Changing the layout or increasing cooling channels is the first usable option because it can influence the temperature distribution of the product. But sometimes this option may not be feasible because of the constraint of mold structure and the available spaces.

The mechanical and shrinkage characteristic properties vary with different plastic material. Some plastic materials tend to have better fluidity so that the melt plastic can fill the mold easily and can be compressed densely and tightly at the same packing pressure. Some materials have a higher strength so that they demonstrate better resistance to deformation. All these favorable plastic properties can result in a low extent of warpage; therefore changing plastic material is the second viable option. However, plastic material application properties and the costs may warrant alternative options in some circumstances.

The third option is to optimize the molding process settings. For example, we can improve the mold and melt temperatures to increase the fluidity of the melt plastic. We can design the packing profile to make the shrinkage rate evenly distributed along the flow path. The packing pressure distribution is uneven along the flow path which will result in different shrinkage rate over different areas. The optimized packing profile will result in the pressure distribution more even along the flow path so that the warpage can be reduced. This method is very useful for products with thick walls. We can also adjust the temperature of each cooling circuits to influence the cooling performance. It can led to some parts of the product solidifies first so that they have higher rigidity. However, this option makes molding process control very complicated and time consuming to stabilize the production process.

Using different mold insert materials is another good approach. The mold has many parts and the material for some parts can be different. The thermal performance varies with different metals. Therefore, we can change the materials of the parts to influence the temperature distribution of the product and finally minimize the warpage of the product.

Case study:

A thorough industrial case study has been carried out with a milk bottle container as shown in Fig 3 which displays the deflection distribution after molding. Clearly this product encountered serious warpage problem. Further verification was done from the product temperature distribution. The side walls warp towards the core and such deformations make the container inside space smaller than required to hold 4 bottles of milk. Initial simulation with the real mold design and process settings showed some areas near the bottom section of the side walls get cold quicker while the middle section cools much slower and this is the reason for the warpage. This is because the bottom inserts for the product is made of Be-Cu while the rest inserts made of tool steel.

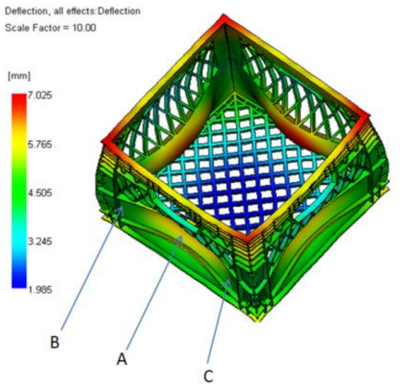

Fig. 3: Warpage of the product verified with simulation.

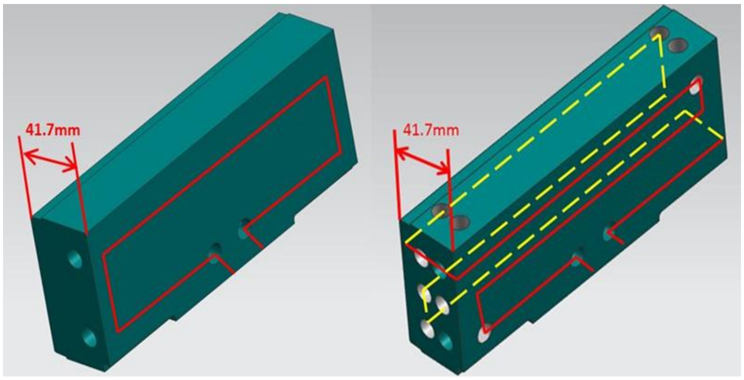

Fig. 4: The original (left) and new cooling circuits (right).

With the support of molding CAE simulation capability, some potential ways to minimize the warpage of the product were explored. One possible way is adding more cooling channels to the side walls so that the temperature will be more evenly distributed over the middle section (see Fig. 4). Although the simulation shows the option was promising, because the mold has already been designed and manufactured at that time, it was soon discovered that the insert parts contacting with the side walls is too constrained to accommodate new cooling channels. Another possible way is optimizing the packing profile. However, for this product, the packing stage only lasts 2 seconds and the gates solidified quickly, so there is no time window to modify the packing profile. Another option is to change the side walls into ribbed geometry whose mechanical strength can be increased; but client logos are supposed to be placed on the four side walls. Moreover, the module to form the side walls is large and the mold insert modification will be complicated and expensive. Increasing the thickness of the side walls might be also useful; but more effective cooling circuit is needed if the wall thickness increases. This resulted in a longer cooling time and will affect the productivity. Further, increase the thickness will increase the plastic material cost too. The most cost-effective way in this situation found was to use different mold insert material with high thermal conductivity for the side modules. So we changed the material of the side parts from H-13 (mold steel) to Be-Cu and the molding simulations were carried out again. The simulation result shows that the warpage can be reduced a lot.

Deflection Points	Point A	Point B	Point C	Warpage
Before improvement	7.00	4.53	4.66	2.405
After improvement	3.75	4.51	4.41	0.710

Tab. 1: Deflections of three representative points before and after using Be-Cu side inserts.

The original deflections of three representative points simulated are shown in Table 1. We defined a warpage measure as the average deflection of at the three points, i.e. $\triangle = (|X_A - X_B| + |X_A - X_C|)/2$. The original warpage was 2.4 mm in this case. After changing the insert materials of the side wall modules, as also seen from Table 1, the warpage has been reduced to 0.710 mm, or 70.5% less.

Conclusion:

In this paper, we proposed a new warpage-fixing mold modification workflow aiming to fix the problem more effectively and quickly with molding process CAE simulation. The new workflow integrated both CAD and CAE process which makes it possible to modify the mold design and evaluate the resulting molding product quality at the same time. With the help of advanced CAE technology, the design verification process has been virtually simulated on computer with different mold modification options. Four possible ways to solve the warpage problem after mold made are proposed; and their pros and cons are compared. The advantage of the four options in this cyclic CAD/CAE simulation method is that it offers insightful engineering scenarios of different mold-fixing options. The proposed method provides guided optimization directions and can shorten the warpage fixing engineering time compared to the traditional trial and error approach. A case study has been presented. After trying different options with molding CAE simulation cycles, eventually, a solution was found by changing mold insert material.

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