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Mold modification methods to fix warpage problems for plastic molding products

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ABSTRACT
Warpage is a common quality problem for plastic molding products and it is influenced by numerous factors. Molding simulation software packages are widely used to analyze the molding conditions. However, the current practice typically addresses the warpage problem at the mold design stage. When the mold has already been manufactured, solving the warpage problem becomes difficult. In this paper, we proposed a simulation workflow aiming to analyze the reasons that cause warpage after pilot molding, and further, four possible methods to resolve such problems. Two case studies are presented to show the available solution options. For those given examples, by using mold inserts of different material and adding more cooling channels respectively, the warpages of the products were solved.

KEYWORDS
plastic injection molding; warpage; molding simulation; CAD/CAE; mold modification

1. Introduction

Injection molding has been widely used in the plastic industry since it is an efficient and cheap way to manufacture products of complex geometry. The injection molding process can be divided into 3 stages, filling, packing and cooling [23]. Warpage is a common quality problem for injection molded products and it is influenced by all these stages. Due to its complexity and numerous influencing factors, warpage is extremely difficult to be avoided with only judgment according to engineers' experience; it is not uncommon that warpage problems occur after mold being made. Nowadays, the advancement of the computer technology makes it possible to simulate the injection molding process with confidence. With the reasonable prediction of molding effect at the difference stages, engineers could gain useful insight to understand how the melt plastic flows into the mold and why a warpage problem occurs. In reality, on the other hand, companies still face the challenges of fixing warpage problems effectively, and more critically so after the mold has been made. Compared to the traditional way of trial-and-error mold fixing method, Computer Aided Engineering (CAE) technology has the great potential to advise engineers on why the faults occur and how to fix such problems without causing significant production delay and incurring too much mold fixing cost. This paper proposes a set of useful methods to address the above industrial challenges by leveraging the advanced CAE technology.

2. Literature review

A lot of researchers have done in-depth research to address warpage problems but most of them focused on the mold design stage with an ideal workflow to minimize the chances of warpage, i.e. starting from plastic part design, followed by molding process analysis to avoid warpage issues, and then finalize the mold design [1],[5],[19]. In the recent years, many works also focused on the optimization of the process parameters during the injection molding process to solve the warpage problem. However, as the injection molding process has so many parameters and for each parameter there are so many levels, the trial and error approach takes a lot of molding or simulation time. That is why almost all of them used the Taguchi design of experiment (DOE) method [3],[9],[17]. For example, Oktem et al. [15] 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 the thin-shell plastic product. Although DOE has been widely used to find the best possible

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combination of the process parameters, the so-called "best settings" found may not be the best process settings in the definition domain. It is not uncommon that after the trail of molding processes, there is no satisfactory solution because the processing rectification has limited effective range for warpage. On the other hand, based on our working experience, it is difficult to precisely control the process parameters as required due to the machine controlling limitation.

Some researchers tried to reduce warpage effect by adding additional ribs to strengthen mechanical performance because using ribs consumes less material than increasing the thickness of the overall product. Yang et al. [24] compared the warpage effects of an original flat plastic part geometry and three other designs of different ribbed geometries via CAE analysis. They found that the warpage decreased significantly if both the geometry and parameters of the ribs are well selected. However, for some products, the aesthetics consideration is as important as the functional performance. For example, some outer surface could not have ribs because the logo is always placed on the flat surface. Clearly ribs will also make the mold more sophisticated and the mold machining will be expensive and longer.

Other researchers explored optimizing the cooling system design to reduce warpage. Cooling stage takes the longest time during the injection molding process, so ineffective cooling system will not only influence the quality of the product, but also result in low productivity [2],[5]. Poor cooling system design will result in unevenly distributed temperature which in turn will cause warpage. Therefore, Agazzi et al. [1] used conjugate gradient algorithm and Lagrangian technique to optimize the cooling system design. However, a lot of things should be considered when design the cooling channels. For example, the cooling channels may interfere with the ejection pins and the cooling channels should be in a reasonable length so that the temperature difference between the inlet and outlet is less than 3°C [13]. Although different optimization procedures can consider some important constrains discussed above but they can be too complicated and may run into non-convergence if many constrains are taken into consideration at a time. For example, so far to the authors' knowledge, there is no optimization program could consider cooling channel machinability.

Nowadays, engineers have more options when designing the cooling channels as the development of advanced manufacturing technology. For example, 3D printing makes conformal cooling channels possible by building the mold insert layer by layer [22]. Traditionally, cooling channels are straight channels which are hardly to achieve uniform distance from the products' surface, so the temperature distribution is more likely uneven. Conformal cooling channels follow the contour of the mold surface, so the distance between the cooling channels and the mold surface is the same along the cooling lines. Consequently, evenly distributed temperature is more likely to be achieved. Shayfull et al. [19] 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. Therefore, warpage can be reduced with conformal cooling channels. However, in terms of economic efficiency, 3D printing for metals is relatively expensive, and not all the companies have easy access to this high-end technology.

Most of the previous research works follow an ideal CAD/CAE mold design workflow to minimize the warpage, which does the CAE simulation first, finds the possible problem and then solves the warpage problem based on the simulation results before the mold design is finalized. However, in industrial practice, not all the companies follow the ideal CAD/CAE mold design workflow. A lot of them are still following the traditional mold design process as there is a barrier for them to access to the advanced computer technology. It is quite common that the mold has already been manufactured and the production is running when the warpage defects are discovered. This situation is usually caused by tight production schedules or the short of engineering analysis capability in companies. In this situation, the typical design approaches reviewed above are no longer applicable. Therefore, there is a need to investigate effective ways to solve the warpage problem when the mold has already been manufactured. This paper proposes a new workflow and four methods to address warpage problems in such situation.

3. Limitations of the traditional methods to address warpage problems when the mold has been made

The traditional way to solve warpage problem after mold made is largely based on the knowledge and experience of the engineers. Typically, when the warpage problem has been discovered, the engineers will modify the mold based on their knowledge and experience. Then the quality of the product could not be guaranteed as the ability of the engineers varies with each other. In most cases, it is a trial-and-error process as 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 testing shots which are necessary and time-consuming to evaluate whether the mold modification is effective by checking the quality of the molded product. If the molded products still have warpage problem, another round of mold modification is required and the testing has to continue until satisfactory products are constantly produced.

The trail-and-error warpage fixing approach after mold made is no longer acceptable to the modern manufacturing. The plastic products upgrade rapidly which requires the mold companies be able to manufacture mold of high quality quickly and economically. Therefore, making any change after the mold has already been manufactured has to have the predictable effect. Unfortunately, it is hard to be said than done. Usually, without an effective methodology, the mold modification process is a guessing game in the first place and it repeats several times until the qualified product is produced. It is also possible that if the mold modification process is not effective, the mold has to be reworked substantially or totally abandoned because the mold can become more and more complicated and yet molding production gets delayed. Therefore, a lot of time and money can be wasted in the mold modification process, which makes the company less competitive in the market.

4. The proposed workflow to address warpage problems after the mold made

The mold modification process can be greatly shortened with the help of advanced molding simulation software, which makes it possible to confidently evaluate the molding quality and process behavior on computers. Compared to the traditional trail-and-error methods, using computers to validate the quality of molding can save a lot of cost and time. Among all the molding simulation software packages used in the molding industry, Moldflow^{TM} is the most successful one and has been used worldwide. It was originally developed by an Australia company, but is now owned by Autodesk [25]. Using such advanced molding simulation tools, companies can simulate how the melt plastic flows into the mold cavity as well as the solidification process afterwards. The software offers analysis results that indicate the possible quality defects and hence the reasons resulting in these problems can be judged by engineers after a series of simulations has been done. After the possible quality problems are identified, the mold CAD model can be modified virtually on computer to address the possible reasons causing the defects and do the simulation again, until the simulation result is fully satisfactory. After that, the real mold can be modified. In this research work, Moldflow^{TM} has been used to evaluate four different mold modification methods so that the quality of molded product can be well predicted before the physical mold modification process.

Although the proposed approach sounds straight forwards, technically, the molding CAE simulation and mold CAD modification process have not integrated yet as these two processes use different data structure, which greatly impeded the interoperability between CAD and CAE software [20],[21]. To achieve the effective CAD/CAE interactions, engineers have to cyclically deal with the CAD model of the mold which only contains the geometrical information, and further carry out the CAE simulations where both the geometrical and non-geometrical information needs to be provided. Ideally, the CAE model should contain the material properties and the process parameters. A lot of researchers proposed different ways to enhance the integration between the design and analysis processes, such as a build-in single CAD/CAE system, or an integrated feature-based representation model, but none of them are matured enough for industrial application and each approach has some limitations [4],[10–12]. For example, Moldflow^{TM} also has the modeling module which allows the users to modify the mold design in its own environment, but compared to the professional CAD software, the efficiency is much lower because some advanced operations are not supported in Moldflow^{TM}. Currently, the commonly-used approach in industry for the integration of CAD/CAE process is through a Neutral Data File (NDF). Commonly used NDFs are IGES, STEP and X-T. Unfortunately, such NDF approach is a problematic way to exchange data between different domains along the product lifecycle. In the current market, it is the reality that different companies use different CAD or CAE software tools. Even though they use the same brand of software tools, they may not use the same versions. Therefore, the barrier exists for the NDF data exchanges between different CAD/CAE tools; and the trial and error approach to fix molding problems after mold has been made is very costly and painful to the industry. To reduce the number of trial and error CAD/CAE iterations, then the strategies for mold modification process can be justified as an important research topic.

The proposed process to address warpage problem after mold made has the following steps: (1) Utilize the CAD model of the plastic product and develop the detailed mold design model with the feeding system, cooling channels; and then export the geometrical entities to the molding simulation CAE software (MoldFlow^{TM}) via a NDF format (X-T was used in this work). This step realizes the transfer of geometrical information from CAD to CAE. (2) Setup CAE analysis conditions. Apply the non-geometrical information, such as

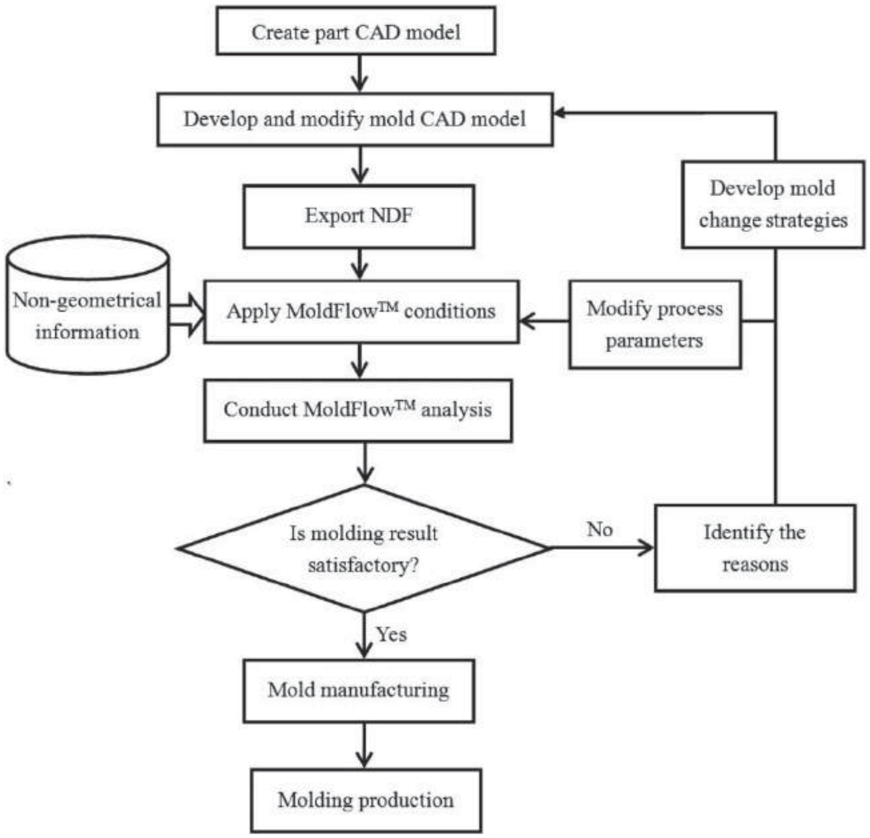

Figure 1. Proposed workflow addressing warpage after the mold made.

material properties and process parameters. Then the simulation is ready to go. (3) Conduct molding process simulation with cooling effect analysis. Based on the simulation results, such as temperature distribution, the causes resulting in warpage can be analyzed and identified. (4) Modify the mold design or the process parameters to address the warpage causes accordingly. (5) Go through the steps from (1) to (4) again in order to verify whether the mold modifications and the new process parameters can produce qualified products. (6) If the result is not satisfactory, iterate the mold design and process modification cycle until high quality product is produced. (7) When the simulated product result meets the design requirement, apply the design modifications to the existing mold. The proposed workflow is shown in Fig. 1.

5. Analysis of warpage influenced factors

The fundamental reason for warpage of the plastic product is shrinkage. It is evitable 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 [16]:

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

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; and

$B(T)$ 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 a plastic material is usually illustrated with PVT (Pressure – Volume - Temperature) curves. Fig. 2 gives the PVT curves of HDPE while the solid black curve highlights the molding part's generic shrinkage characteristics. This characteristic curve is referred to molding shrinkage characteristic curve. The curve shown in Fig. 2 is developed with reference to Moldflow™ material library [14]. Fig. 3 shows the HDPE molding shrinkage characteristic curve with one more dimension,

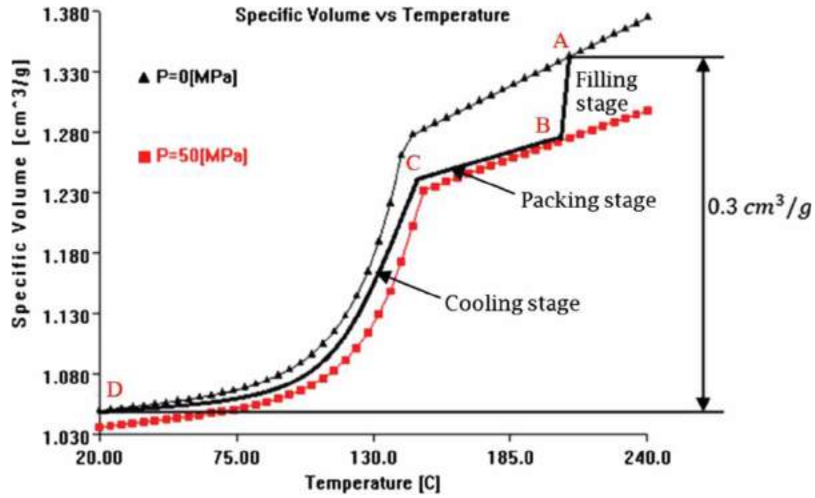

Figure 2. PVT curves of HDPE under different pressures [14].

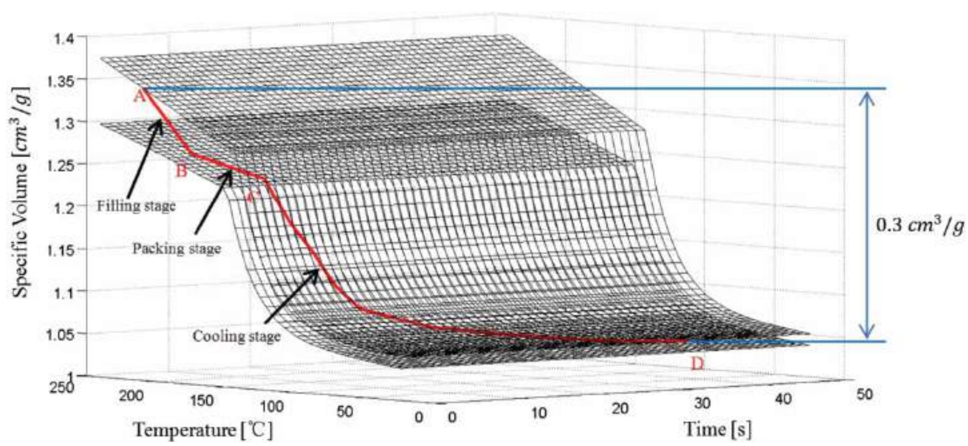

Figure 3. 3D specific volume curve of typical HDPE.

i.e. molding time. HDPE is a commonly used material in the plastic industry because of its excellent mechanical performance and chemical resistance [7].

The thermal-mechanical process history of the molding part and the mold constrains determine the warpage behavior of the product. During the filling stage (A-B shown in Figs. 2 and 3), the plastic melt is injected into the mold at a high temperature to ensure the high fluidity so that it fills the mold easily. The pressure at the gates of the mold increases gradually to overcome the flow resistance in cavities during filling stage. Refer to Fig. 3, assume the melt temperature is set to 210°C and the packing pressure 50 MPa which are the same as the recommended process settings for generic HDPE [14]. When most of the cavity is filled, the molding machine still maintains a high level pressure for a short period of time which is known as the packing stage. The packing stage is shown by the B-C segment shown in Figs. 2 and 3. During the packing stage, the pressure remains almost the same but the temperature decreases gradually to ensure the gate solidified at the end of the packing stage. Then, the coolant flows into the cooling system and removes most of the heat during the cooling stage (C-D shown in Figs. 2 and 3). At the same time, the molded product begins to solidify and both the temperature and pressure decreased until ejection. After ejecting the part out from the mold, the product continues to cools down until the room temperature.

Theoretically, the specific volume change of HDPE during this process is shown in Figs. 2 and 3, i.e. approximately 0.3 cm^3/g. However, 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, which is less than the plastic product. Therefore the strain within the plastic part is created and the residual stress accumulated in the molded product. After being ejected out from the mold, there is no more mold constrains and hence the unevenly distributed residual stress will be released and this release makes the product deviate from the cavity shape and produces 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. The structure of the product has a significant influence on the warpage of the molded products. Products with thicker wall will have higher mechanical strength to resist warpage, but unevenly distributed wall thickness will worsen the situation. Large flat face has a higher risk of warpage which should be avoided and changed into ribbed structure as the ribs have higher rigidity. However, for some products it is unrealistic to add ribs to flat faces because of the aesthetics consideration. Therefore, both functionally and aesthetically consideration should be take into account when design the product. Corners tend to have a higher risk of warpage because it is hard for the cooling channels to remove heat effectively in the corners, so the heat tends to be gathered. Therefore, the cooling effect might be poor and asymmetric. Also, corners have a lot of mold constrains which will have a higher chance of un-uniform shrinkage. We should give special consideration to the sharp corners when design the product.

In the mold design stage, both the location and size of the gates will influence the final shrinkage of the product. Inappropriate selection of gate types and sizes will result in product warpage. Compared to the filling end of the product, areas near the gates tend to have smaller shrinkage rate as better packing effect can be achieved. The gates will solidify too early if the size of the gates is too small. In such circumstances, the packing pressure could not reach the end of filling, therefore, the product could not be fully packed and warpage will be resulted.

The cooling system design is extremely important as it affect warpage phenomena dominantly. The cooling system should remove the heat quickly and make the temperature evenly distributed over the product. The efficiency of cooling system can be measured by heat flux distribution. It not only indicates how much heat can be removed during a unit time through a unit area, but also the cooling effect differences among regions. Although a cooling system with high heat flux is preferred as it can shorten the cycle time, poorly designed cooling system will result in unevenly distributed temperature which will result in warpage of the product after ejection.

The ejection system will also influence the warpage of the product. The molded product needs to be ejected out at the end of the cooling stage. Usually, the product is still at a high temperature and not fully solidified inside when it is ejected out in order to shorten the cycle time. Therefore, the product will deform too much if the ejection force is too high and unbalanced, which will result in unacceptable warpage of the product.

6. Proposed methods to fix warpage problems after mold made

The authors believe that there are four promising methods in this situation to minimize warpage: (1) modifying cooling channels; (2) changing the plastic material used; (3) optimizing molding process setting parameters; and (4) using a different material for 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 warpage problems with quantitative and predictive measures by using these methods comprehensively.

6.1. Modifying cooling channels

Changing the layout or increasing cooling channels is a promising option because it can effectively influence the heat removal flux and temperature distribution of the product. The heat exchange flux q'' is the heat transferred per unit area in unit time and it is expressed as [6]:

$$q'' = \frac{q}{A} \tag{2}$$

in which

q is the total heat transferred in unit time;

A is the surface area.

Each cooling circuit should have a reasonable length and remove more heat with less temperature raise. In many cases, enhancing cooling circuit layout helps to address warpage issues. The common limitations of this method are the constraint of complex mold structure and the available spaces. For example, sometimes it is impossible to modify the cooling channel layout as the mold is so much compacted with sub-systems that no more space for new cooling channels. Further, changing the cooling channel layout may be difficult after the mold has been made because the cooling channels are distributed in many different inserts and modules, and they may need to be redesigned too. For example, additional cooling channels could spatially collide with ejectors.

6.2. Changing plastic material

Warpage problem can also be addressed by using different plastic materials because that there exist many choices with large variations of mechanical properties and shrinkage characteristics. Some materials tend to have better fluidity so that the melt plastic can fill the mold easily and can be compressed tightly at the packing stage. 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. Note that the molding process parameters vary for different materials, their optimization needs good effort too.

Commonly used plastic materials are HDPE, PP, ABS, POM, PMMA, PC and PVC and their recommend process parameters and mechanical properties are shown in Tab. 1 [14]. When choosing a material, its application properties and cost need to be evaluated in addition to the moldability. For example, PVC has excellent mechanical behavior and a PVC product tends to have less warpage compared to HDPE; this is because that PVC has much less specific volume difference during the injection molding process. For PVC (see Figs. 4 and 5), under the recommended process settings, the specific volume difference is only 0.05 cm^3/g while HDPE has 0.3 cm^3/g as mentioned previously. Therefore, the strain and residual stress in an identical PVC part are much less comparing to a HDPE counterpart. However, PVC is not suitable for food contacting products. When the temperature goes up, PVC molecules may decompose and then release chloride ions which are poisonous and harmful to human health.

Table 1. Common plastic materials used in injection molding process [14].

Material	Mold temperature range(°C)	Melt temperature range(°C)	Ejection temperature (°C)	Elastic modulus 1st principal direction(MPa)	Shear modulus (MPa)
HDPE (T50–4400)	20–95	180–280	100	911	319.4
PP (A-333)	20–80	200–280	93	1634.35	591.477
ABS (6003)	25–80	200–280	88	2000	694.444
POM (Tenac3010)	40–90	190–210	142	2987.13	1008
PMMA (KT-80)	40–90	220–280	95	2700	980
PC (PC X-1)	70–120	260–293	127	2280	804.5
PVC (HTX6220)	21–37	180–210	70	3280	1155
PVC (FPVCFN01)	20–70	160–220	75	3280	1155

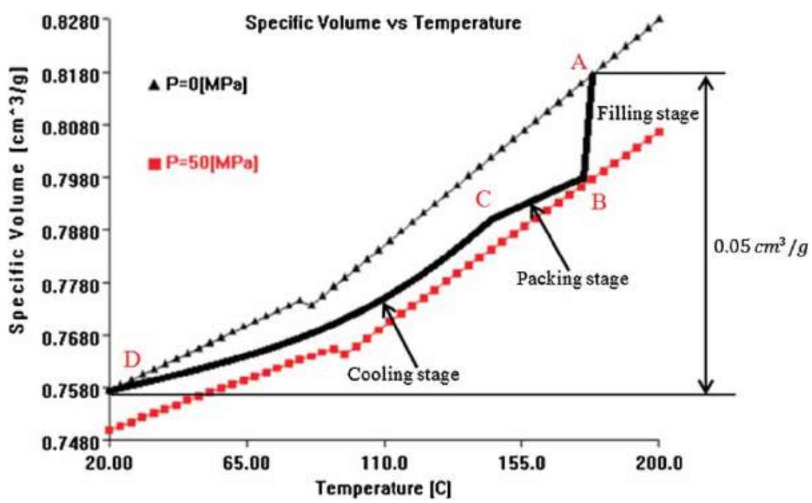

Figure 4. PVT curve of generic shrinkage characterized PVC [14].

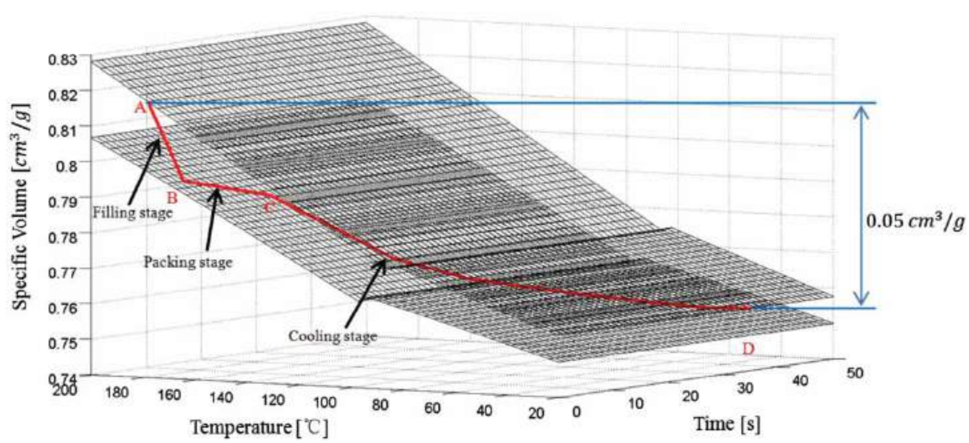

Figure 5. 3D specific volume curve of typical PVC.

6.3. Optimizing molding process setting parameters

Warpage issue can also be reduced by optimizing the molding process settings. The injection molding process can be controlled by a set of parameters either manually or automatically with the molding machine controller; some of them have direct influence on the extent of warpage on the product. Modifying the process parameters could be a good option when modifying mold is more costly and time consuming, especially when the mold has already been manufactured.

High mold and melt temperatures will make the plastic melt has a high fluidity during the filling stage, so that the mold can be filled easily. High packing pressure at optimized level will ensure sufficient plastic melt flows into the mold so that the mold can be fully filled and the product can be tightly compressed. However, if the packing pressure is too high, severe residual stress will be accumulated in the product which will result in a higher risk of warpage. The packing time also need to be optimized so that both the quality and productivity of the product can be assured. If the packing time is too short, the product could not be fully compressed, sometimes the melt plastic will even flow backward into the nozzle. After the gates have solidified, extending packing time does not help for molding quality improvement.

In industrial practice, it is also feasible to 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 is only a remedy option because it makes molding process very complicated to control and time consuming to stabilize. Another promising approach is optimizing the packing profile to make the shrinkage rate evenly distributed along the flow path [8]. As mentioned previously, the packing pressure distribution is uneven along the flow path which will result in different shrinkage rate over different areas. The optimized packing profile could 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.

6.4. Using a different material for mold inserts

Using a different material for mold inserts is another promising approach. A mold has many parts and the materials for some parts can be different. As mentioned previously, the thermal performance varies with different metals. There are some metals whose thermal conductivities are much higher than typical mold steels. The heat flux q'' in this situation is expressed as [18]:

$$q'' = -k\frac{dT}{dx} \tag{3}$$

in which,

k is thermal conductivity;

T is temperature of the product; and

$\frac{dT}{dx}$ is temperature gradient.

Therefore, high thermal conductivity enables them to remove heat more effectively because of the heat flux increases linearly with thermal conductivity. Usually, due to the cost reason, high heat-conducting materials are only used for individual mold inserts in a cooling system to enhance heat removal in some specific areas. Tab. 2 compares the thermal performance of some typical metals [14]. Based on the observation, changing the material of the parts is proposed to influence the temperature distribution of the mold and finally minimize the warpage of the product.

Table 2. Thermal performance of some typical metals [14].

Material	Specific heat (J/kg°C)	Thermal conductivity (W/m°C)	Coefficient of thermal expansion (1/°C)
P-20	460	29	1.2e-005
H-13	462	29.8	1.04e-005
Copper (pure)	380	388	1.76e-005
Al	880	190	2.39e-005
Be-Cu	360	130	1.7e-005

7. Case study 1

A thorough industrial case study sponsored by a Canadian plastic molding company is carried out with a container to carry milk bottles. This product, named as Milkcrate, encountered serious warpage problem which has already influenced its functionality. As shown in Fig. 6, the side walls warp towards the core and make the inside space not enough to hold 4 bottles of milk. When we got this project, the mold has already been designed and manufactured. Therefore, it was required to minimize the changes on either the Milkcrate model or the mold design because such changes would be extremely expensive and time consuming to do so.

As the real production scenario is so complicated, to build up the basis of confidence for Moldflow™ simulation results, the initial simulations using the real mold design and initial process settings were carried out. The mold configuration is shown in Fig. 7 and the results are shown in Figs. 8 and 9. Comparing Figs. 6 and 8, it can be observed that the warpage pattern is tally to the real product and the deformation amount simulated is approximately reflect the actual value within a tolerance of +/−

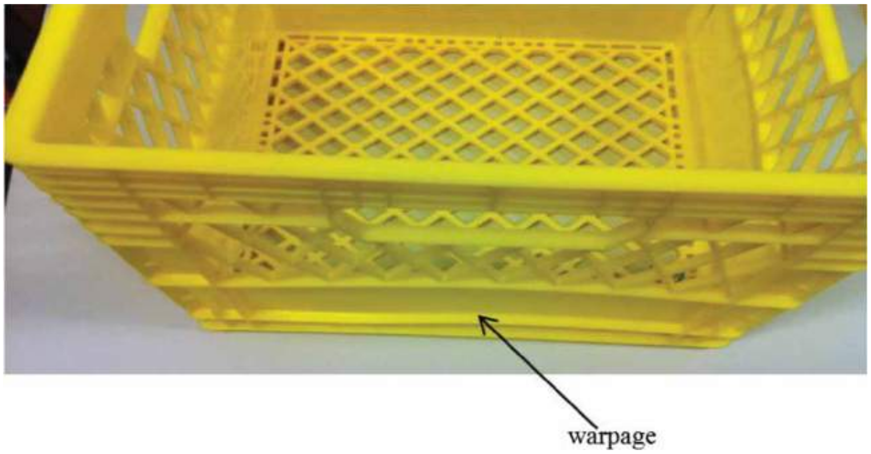

Figure 6. Warpage of Milkcrate, a real product.

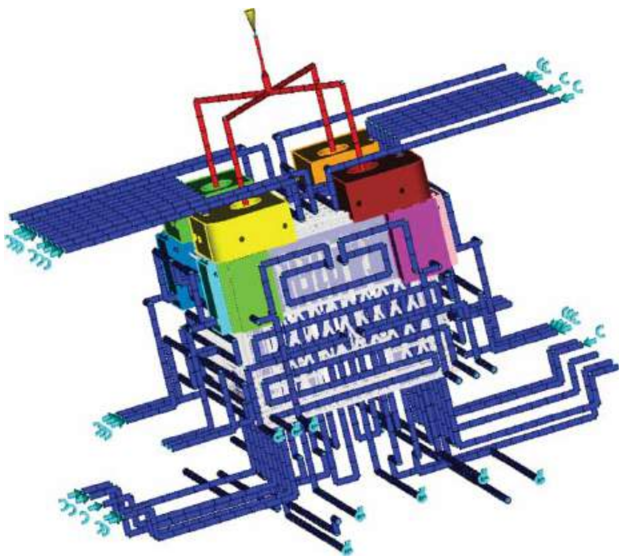

Figure 7. Mold configuration of Milkcrate.

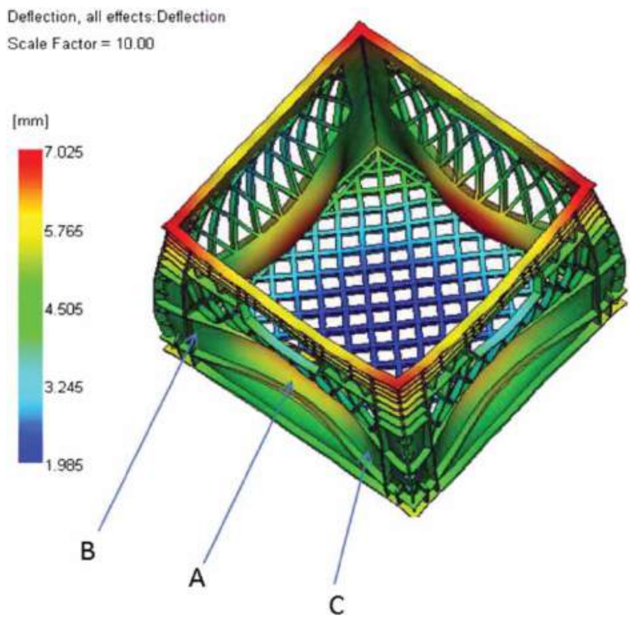

Figure 8. Warpage of Milkcrate (initial simulation).

20%; hence it can be concluded that Moldflow^{TM} is an effective tool to predict warpage. Fig. 9 shows that the temperature distribution of the Milkcrate was uneven. Some areas near the bottom section of the side walls get cold quicker while the middle section cools much slower. This was because 12 Be-Cu inserts were used in the bottom areas of the mold. As can be seen in Tab. 2 that Be-Cu has a very high thermal conductivity compared to the mold steel, which makes the areas contacting with Be-Cu inserts solidified quickly and this is an important contributing factor for the warpage.

With the support of molding CAE simulation capability, some potential ways to minimize the warpage of Milkcrate were explored. One possible way suggested was to add more cooling channels to the side walls so that the temperature would be more evenly distributed over the middle section. After simulating the original and the enhanced designs of cooling channels as shown in Fig. 10, the result was shown in Fig. 11. It can be seen that the warpage quality improved a lot. The simulated deflections of three representative points for the original and the new design of the cooling channels are shown in Tab. 3.

We define warpage as the maximum relative deflection of the three points A, B, and C on the interested face of the product: Points B and C are two furthest points with minimum deviation which form a reference base line; Point A is the maximum deviation point from the reference base line measured in the direction normal or perpendicular to the selected face. In a mathematic formula, after discounting the material shrinkage, the warpage is measured

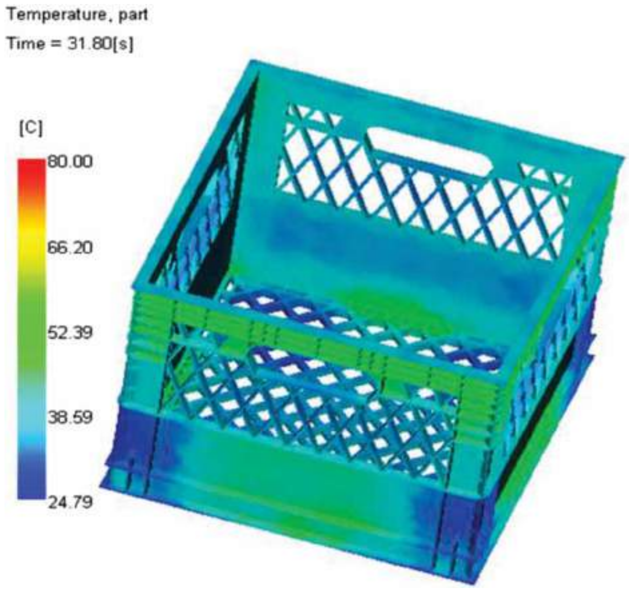

Figure 9. Temperature distribution of Milkcrate (initial simulation).

as the following:

$$\overrightarrow{\Delta} = (|\overrightarrow{X_A} - \overrightarrow{X_B}| + |\overrightarrow{X_A} - \overrightarrow{X_C}|)/2$$

Where $\overrightarrow{X_p}$ is the coordinates of the specific point, p represents the characteristic points, i.e. A, B, or C. $|\overrightarrow{X_A} - \overrightarrow{X_B}|$ stands for the resulted vector component along the face normal direction.

In this definition of warpage, only the deviation along the normal direction of the face is considered because other orthogonal components are relatively small. As shown in Fig. 8 and Tab. 3, the warpage can be worked out as 2.405 mm for the initial simulation. After adding more cooling channels, the warpage of Milkcrate improved, i.e. it has been reduced to 1.468 mm, or 38.96%. However, the mold has already been designed and manufactured at that time. It can be seen from Fig. 11 that the insert parts contacting with the side walls is only 41.7 mm and the diameter of the cooling channels is 11 mm which is too constrained to accommodate new cooling channels. In terms of manufacturing, re-machining is also very difficult and expensive to implement more cooling channels in these parts.

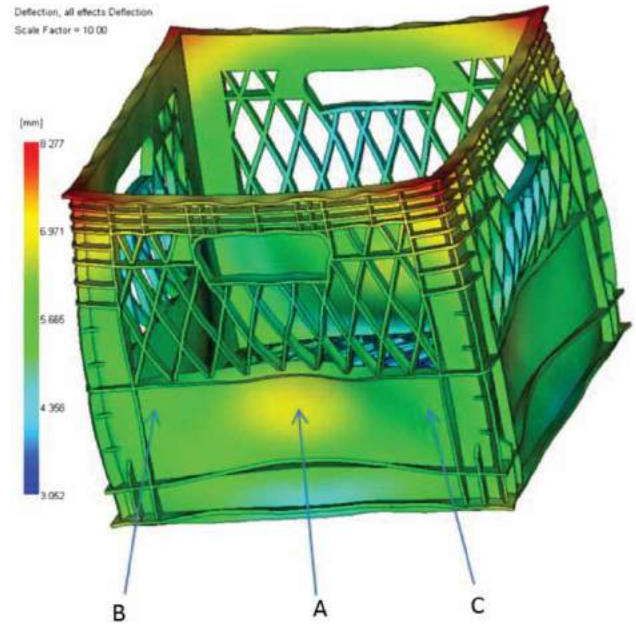

Figure 11. Warpage of Milkcrate (with the enhanced cooling channels).

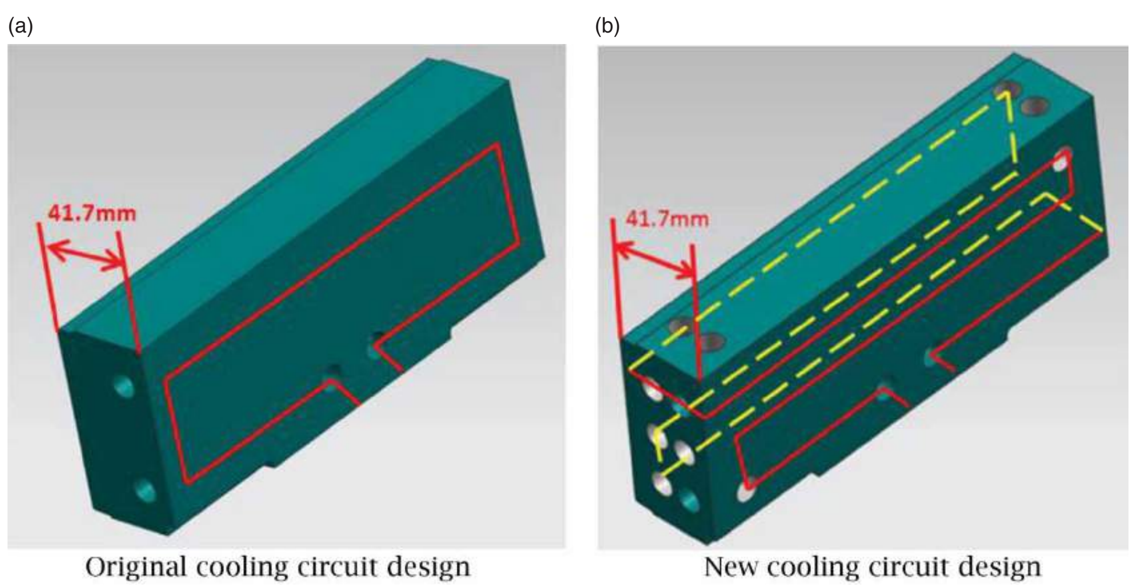

Figure 10. Original and new design of the cooling circuit.

Table 3. Deflection of three representative points.

Deflection Points	N515704(X_A)	N515120(X_B)	N515232(X_C)	Warpage
Simulated deflection from the original model (mm)	7.00	4.53	4.66	2.405
Simulated deflection with enhanced cooling channels (mm)	6.818	5.373	5.328	1.468

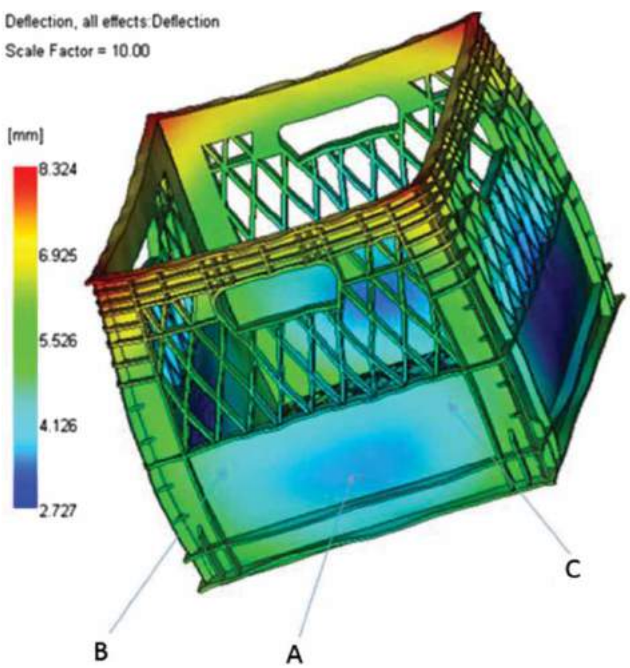

Figure 12. Warpage of Milkcrate with changed side inserts (simulation).

Another cost effective way found for this case study was using different mold insert material with high thermal conductivity for the side modules. Most parts of the mold are made of H-13 (mold steel) whose thermal conductivity is 29.8 W/m°C. For Be-Cu its conductivity is 130 W/m°C which is much higher than H-13. Based on Equation 3, by using Be-Cu, the cooling efficiency can be improved 3.36 times. So the simulation with Be-Cu side parts was carried out. Warpage deflections with changed side inserts are shown in this Fig. 12. We can see the warpage can be reduced a lot. As also seen from Tab. 4, the warpage of the product, after changing the side insert material, has been reduced to 0.710 mm, or 70.48% less than the original design.

Other approaches of enhancement attempted include changing the plastic material for the product and optimizing the molding process settings, due to the limitation of space, the results are to be reported in another separate paper in the future.

8. Case study 2

Here is another case study with a Tray product manufactured by the same manufacturer. The Tray is a thin wall plastic product used to carry mails. As can be seen in Fig. 13, this product has a lot of edge blends and holes,

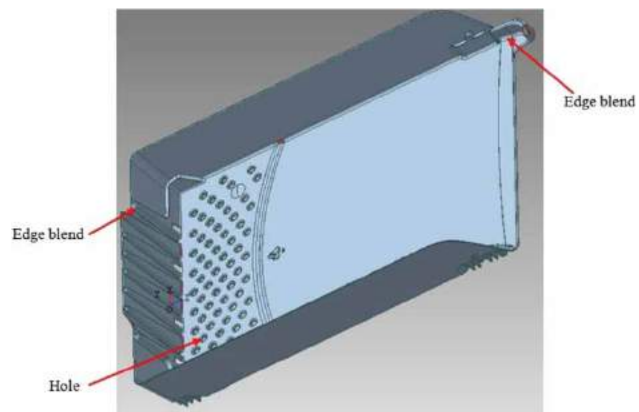

Figure 13. CAD model of Tray.

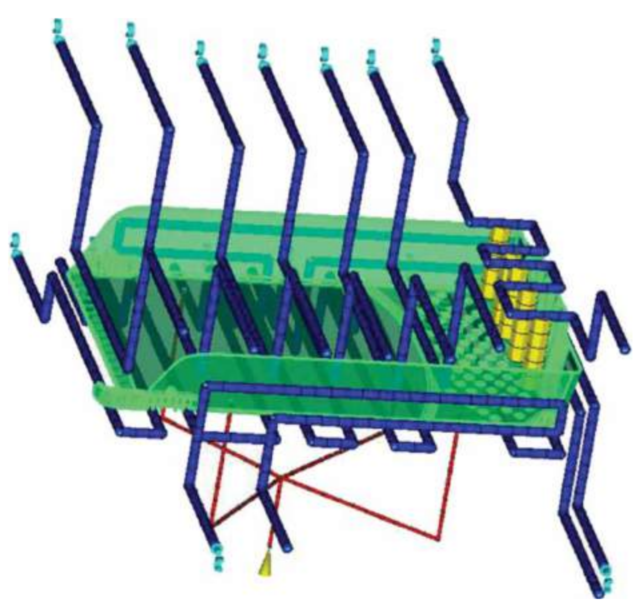

Figure 14. Mold configuration of Tray.

Table 4. Deflection of three representative points with side inserts.

Deflection Points	N349820(X_A)	N349870(X_B)	N349767(X_C)	Warpage
Simulated deflection with changed side inserts (mm)	3.75	4.51	4.41	0.710

which makes it extremely complicated. When we got this project, the mold has already been designed.

The initial simulation was conducted using the real mold design and initial process settings. The mold configuration is shown in Fig. 14 and the Moldflow^{TM} simulation results are shown in Figs. 15 and 16. Fig. 15 shows that this product has a large chance of warpage. The side walls bowing towards the center of the product. From Fig. 16 we can see that the temperature distribution of the product is highly uneven. The inner wall has a higher temperature compared to the outer wall. This is because the inner wall is formed by the core which is in the middle of the mold and that region is difficult to remove the heat although the cooling channels at the core side have 5 baffles which are designed to remove heat quickly. The temperature distribution in Fig. 16 indicates that the cooling efficiency at core side is inadequate. At the same time, due to the semi-open structure, there is no support when the product shrinks. Poor mechanical strength together with the uneven temperature distribution results in the warpage after ejection.

Again, with the support of molding CAE simulation capability, more cooling channels were added to the mold design to minimize the warpage of Tray so that the temperature difference between the inner and outer side walls can be reduced. After checking the availability of space

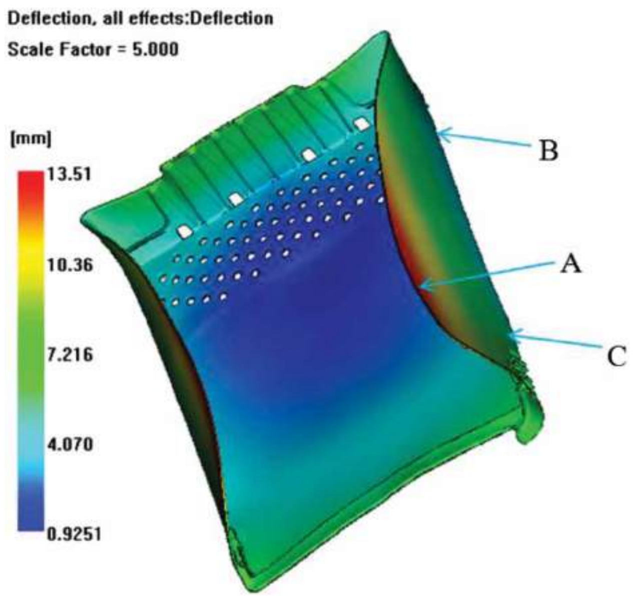

Figure 15. Warpage of Tray (initial simulation).

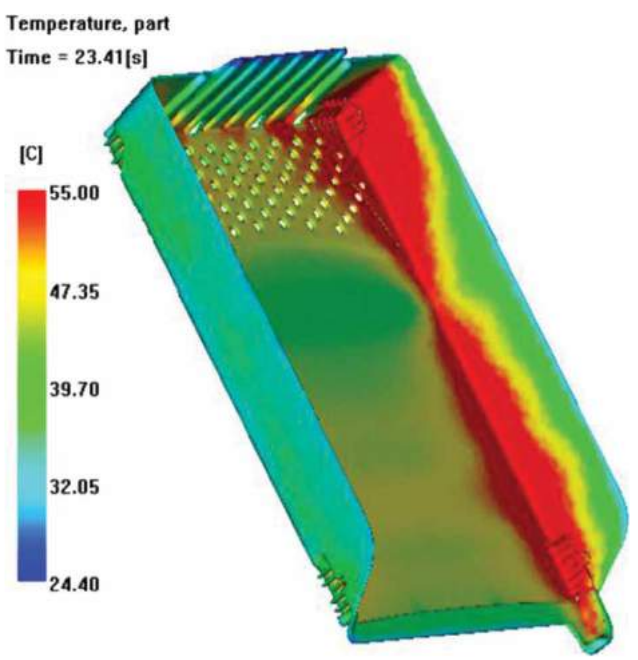

Figure 16. Temperature distribution of Tray (initial simulation).

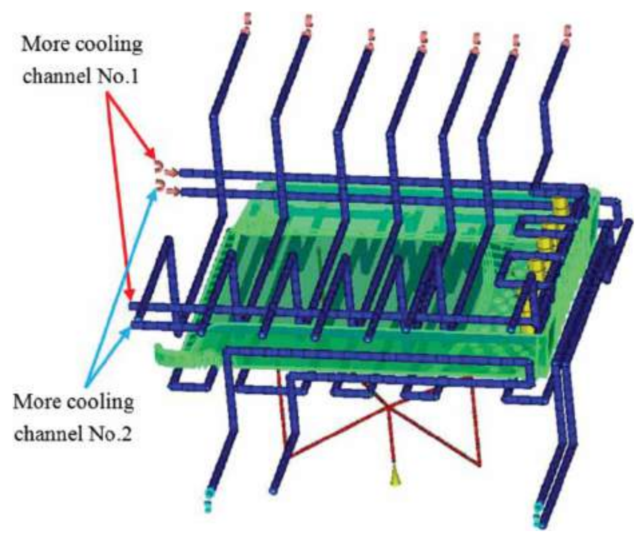

Figure 17. Configuration of the Tray (more cooling channels).

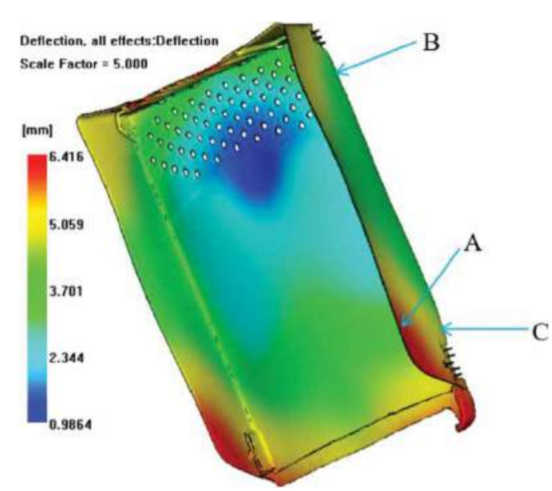

Figure 18. Warpage of Tray (after adding more cooling simulation).

Table 5. Deflection of three representative points.

Deflection Points	N191578 (X_A)	N212055 (X_B)	N211030 (X_C)	Warpage
Simulated deflection from the original model (mm)	13.44	4.36	4.70	8.91
Simulated deflection with more cooling channels (mm)	5.01	4.12	3.98	0.96

and spatial collide with other modules, two more cooling channels at the core side were added as shown in Fig. 17. Then the molding simulation showed that the warpage has been reduced by 40%, but still could not be accepted. Then, decreasing the coolant temperature of the core side (marked in pink in Fig. 17) is tried. The simulation result is shown in Fig. 18. It can be seen that the warpage quality improved a lot. The deflections of three representative points for initial and more cooling channels simulation are shown in Tab. 5. Following the warpage definition mentioned above, the warpage for the initial simulation is 8.91 mm. After adding more cooling channels, the warpage of the Tray has been reduced to 0.96 mm, or 89.23%.

9. Conclusion

In this paper, we proposed four warpage-fixing methods aiming to solve the common problem more effectively and quickly after the molds have been made with integrated CAD and molding CAE simulation cycles. The design change effectiveness has been virtually simulated on computer with different options. This CAD/CAE coupling analysis capability greatly shortens the warpage fixing engineering cycle compared to the traditional trial and error method. Two industrial case studies are presented. The findings of this cyclic CAD/CAE simulation research offer insightful engineering scenarios of different mold-fixing options. A recent update we heard form the company was that the solution proposed by us to address the Milkcrate case has been proven effective by a new mold set for the same product with new mold insert design of more thermal conductive material; and the warpage problem has been solved. In conclusion, the proposed methods can guide optimization directions and shorten the warpage fixing engineering time in industrial applications.

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