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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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ABSTRACT

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