Autodesk® Moldflow Insight 2024

Validation of 3D Warp Accuracy

Executive Summary

The Autodesk Moldflow Insight 2024 and Autodesk Moldflow Adviser 2024 software releases include improvements in the 3D Flow and 3D Warp solvers for more accurate prediction of warp and residual stress for fiber-reinforced polymer compounds and Liquid Crystalline Polymers (LCPs).

In addition, Moldflow Insight 2024 includes the option to use a new shrinkage model known as the "*Shrinkage Test Adjusted Mechanical Properties*" (STAMP) method for 3D meshes. This model makes use of measured shrinkage data to calibrate the mechanical properties of the polymer to achieve improved prediction accuracy of the residual stress, shrinkage magnitude and shrinkage anisotropy, and therefore to improve warp deflection prediction accuracy.

The changes in the 3D warp deflection predictions for the residual stress model and the new STAMP shrinkage model are validated in this report using a large dataset of measured shrinkage values from shrinkage test plaque molding, as well as using measured deflection data from molding case-studies of complex parts.

Contents

Introduction

Change in 3D Residual Stress calculations

The residual stress calculation during a 3D Fill+Pack analysis has been changed for semi-crystalline polymers with fiber fillers and for all LCP compounds (including those without fiber reinforcement). The 3D warp calculation uses the residual stresses as an input to predict final part deformation. This change improves the anisotropy of the shrinkage prediction which is a contributor to warp deflection by modifying the way that the temperature dependency of the coefficient of thermal expansion is estimated for semi-crystalline materials from the temperature dependence of solid-phase Pressure-Volume-Temperature (PVT) data. This leads to changes in prediction of shrinkage magnitude which are most noticeable in the flow direction, where shrinkage values are usually quite low for fiber-filled compounds due to the strong fiber alignment in the flow direction. This change improves the warp prediction accuracy for 3D mesh types for both the Moldflow Insight 2024 and Moldflow Adviser 2024 products.

3D Warp calculations utilizing the older Generic Shrinkage model are not affected by these changes.

STAMP Shrinkage Calibration Method

The key thermo-mechanical material properties used to calculate the residual stresses from a flow analysis and therefore drive the warp analysis, are the modulus, Poisson’s Ratio and Coefficient of Thermal Expansion (CTE). In the case of polymer compounds with fiber inclusions, these properties are anisotropic due to the alignment of the fiber inclusions. The properties of polymers without fiber inclusions often also exhibit some degree of anisotropy due to alignment of the crystalline and molecular structures.

When not using a shrinkage calibration model, representative mechanical properties can be obtained for each specific polymer compound by characterizing molded samples in laboratory measurement procedures using standard tensile test (modulus and Poisson's Ratio) and thermomechanical test (CTE) devices.

The STAMP Shrinkage model [1] calibrates these mechanical properties by using measured shrinkage data obtained from rectangular plaque moldings. This is the same shrinkage molding data which is also used to calibrate the CRIMS [2] and Residual Strain Shrinkage models for use in Midplane and Dual Domain analyses.

During shrinkage characterization of each polymer, moldings are made at three different plaque thicknesses, with variations in packing pressure, injection speed and melt temperature at each thickness. Due to the unidirectional flow which occurs during the filling of this end-gated cavity, the paired set of directional shrinkage measurements for each sample are described as being in the flow direction and the direction "transverse" to flow. Fiber inclusions are strongly aligned in the flow direction.

This measured shrinkage data is available for over 5000 polymer materials in the Moldflow public material database, as well as many confidential polymers, representing many years of shrinkage characterization tests. The STAMP model makes use of this data to improve the warp prediction accuracy of 3D analyses without requiring the retesting of polymers for which shrinkage characterization for CRIMS had previously been performed.

The first step in the STAMP method is the calibration of so-called compressibility values, which express the sensitivity of measured shrinkage outcomes to the packing pressure. Calibrated compressibilities are determined in both the flow and transverse directions based on the respective shrinkage measurements in those directions as follows:

$$C_i = \frac{\sum_{j=1}^{N_i}(S_{i,j}-\bar{S}_i)*(P_{i,j}-\bar{P}_i)}{\sum_{j=1}^{N_i}(P_{i,j}-\bar{P}_i)^2} \qquad (1)$$

Where for either the flow or transverse direction, C_i is the compressibility for a series of moldings i which vary only by packing pressure; N_i is the number of moldings in that series; $S_{i,j}$ and $P_{i,j}$ are respectively the measured shrinkage and cavity packing pressure of each molding in that series and $\bar{S}_i$ and $\bar{P}_i$ are the average shrinkage and cavity packing pressure of the series i.

Once the calibrated compressibilities have been determined for each measurement direction, the calibrated CTE for each direction can be calculated according to:

$$\alpha_j = \frac{S_j + C_i P_j}{T_{sol} - T_{room}} \qquad (2)$$

Where for either the flow or transverse direction, α_j is the calibrated CTE from the jth molding, P_j is the cavity packing pressure of that molding condition, T_{sol} is the solidification temperature and T_{room} is the room temperature at which the shrinkage samples were measured.

For polymer composites which contain fiber reinforcements, the goal is calibration of the polymer matrix properties of modulus, Poisson's Ratios and CTE. Anisotropic, locally varying properties of the polymer compound are then calculated by micro-mechanics using these calibrated polymer matrix properties, plus the known properties of the fiber and the local fiber orientation prediction [3, 4].

Calibrated properties of the polymer matrix are obtained through an automatic iterative process of optimization in which the objective function to be minimized is the error in matching the calibrated compressibilities and CTE values of the compound (from Equations 1 & 2). Details of the calibration process are available in US patent application 17/959,221.

Solver Options

In the Autodesk Moldflow Insight 2024 software, the STAMP shrinkage model for 3D analyses can be selected on the *Shrinkage Properties* tab of the material data dialog (see Figure 1). This selection is only valid for materials which have measured shrinkage data. Additional shrinakge molding process information is included in the material data to support the STAMP calibration process. Therefore, to use STAMP in an old study file, it is necessary to reimport the material data into the study from the Moldflow 2024 database or updated udb files.

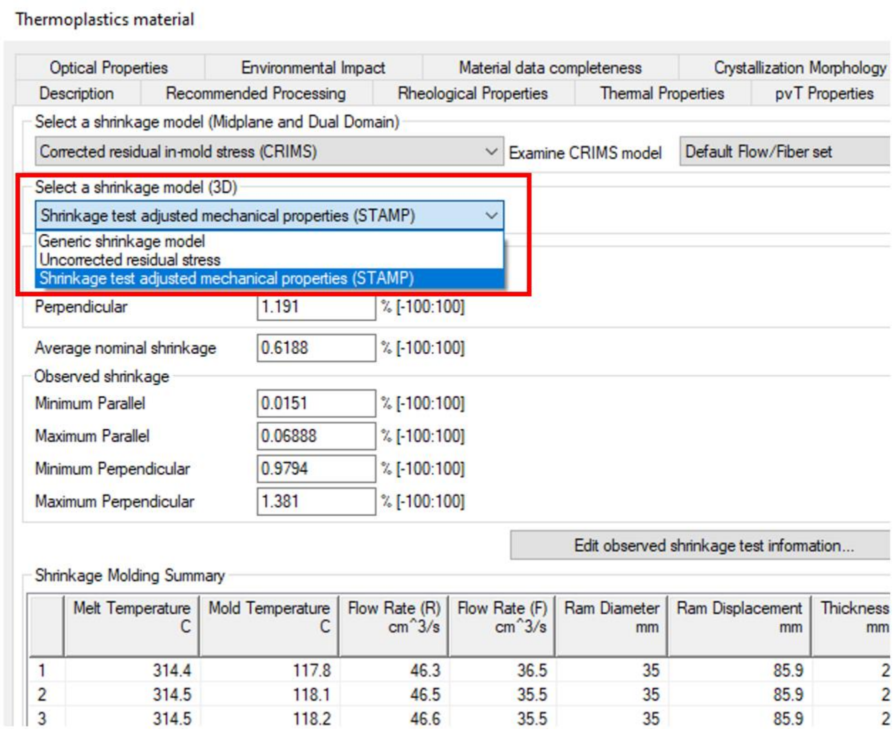


Figure 1: Shrinkage model selection in the Material properties dialog

Verification and Validation

Comparison with shrinkage molding data

Validation of the Change in the Uncorrected Residual Stress model calculation

Measured shrinkage data obtained in the Autodesk Material Laboratory for 105 fiber reinforced polymer compounds was used to validate the change in residual stress calculation in 3D Fill+Pack analyses and the subsequent shrinkage and warpage predictions. For each material, shrinkage was measured in the flow and transverse directions for 25 molding conditions of the rectangular test plaques which are also used to calibrate the CRIMS and STAMP shrinkage models. The 25 molding conditions include variations in thickness, injection speed, packing pressure and melt temperature. In this validation test, the measured shrinkage data is used to validate the Uncorrected Residual Stress model changes, without using the shrinkage data to modify or calibrate any material properties or residual stress values.

Figure 2 shows a comparison of the measured flow direction shrinkage in the rectangular plaques with the flow direction shrinkage predicted by the Uncorrected Residual Stress model. Each point represents the shrinkage values (predicted and measured) of one of the molding conditions for a polymer material. All 25 molding conditions for 105 fiber filled polymers are presented on the graphs. The graphs also include a diagonal line which represents a 1:1 equivalence between the measured and predicted values. Data points which are close to the diagonal line are those for which the prediction closely matches the measured value. Data points above the line are cases where the shrinkage is over-predicted. The prediction vs. measurement comparison for both Moldflow 2023 and Moldflow 2024 are presented side by side to highlight the prediction change in the 2024 release. While the predicted shrinkage for amorphous and Polypropylene (PP) based polymers are largely unchanged, there is strong trend of improved accuracy due to reduced flow direction shrinkage for the non-polypropylene semi-crystalline polymers.

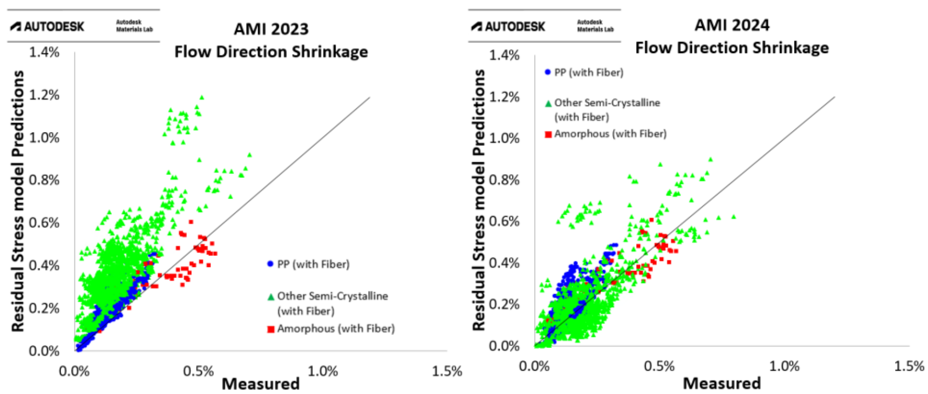


Figure 2: Flow Direction Shrinkage, measured vs prediction comparison for Moldflow 2023 (left) and Moldflow 2024 (right)

Figure 3 shows the corresponding comparisons for shrinkage in the transverse direction. For the transverse direction there are only moderate changes in the predicted shrinkage in the Moldflow 2024 release compared to the previous software version. Notice also that the shrinkage values in the transverse direction are typically much larger than the shrinkage in the flow direction due to the strong alignment of fibers in the flow direction.

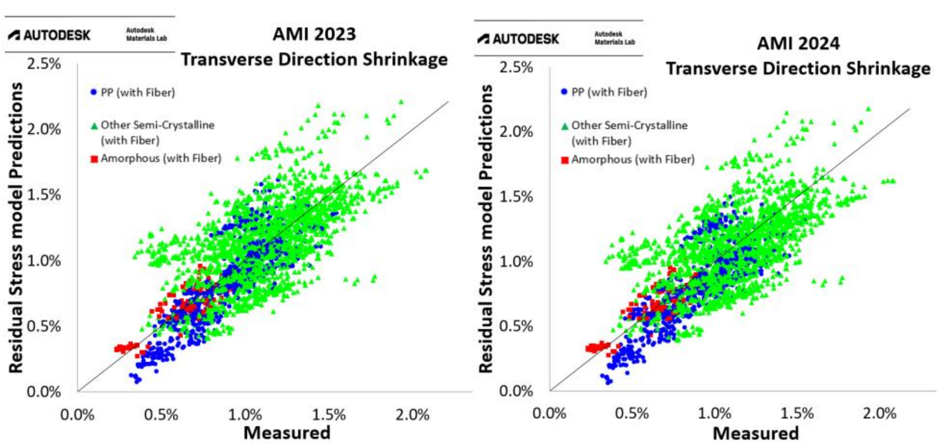


Figure 3: Transverse Direction Shrinkage, measured vs prediction comparison for Moldflow 2023 (left) and Moldflow 2024 (right)

Uncorrected Residual Stress model predictions for polymers without fiber-filler are not changed in the Moldflow 2024 release, apart from the LCP polymers which have high anisotropy even without fiber reinforcement due to their highly aligned crystalline structure.

Validation of the STAMP calibration model

The shrinkage prediction accuracy of the new STAMP shrinkage calibration model for 3D analyses has been validated using the same molded shrinkage data which is used to calibrate the mechanical properties during the STAMP procedure. These validations have also been compared to the validations of the Uncorrected Residual Stress model to demonstrate the superior prediction accuracy of the STAMP model.

Figure 4 and Figure 5 show respectively the flow direction and transverse direction shrinkage comparisons between measured shrinkage from actual moldings and the predicted shrinkage for 171 polymers which do not contain fiber fillers. Of the 171 materials, 61 are amorphous, 70 are polypropylenes (PP) and 40 are other semi-crystalline materials. 90 of these polymer grades had no filler, while 61 had talc filler, 19 had some other spherical mineral filler and one had glass bead filler. 25 molding conditions including variations in thickness, packing pressure, injection speed and melt temperature are included for each polymer. Predicted shrinkage values from the Moldflow Insight 2024 release are shown for both the Uncorrected Residual Stress model and the STAMP calibration model. The solid diagonal line is a reference line showing the target equivalence between the measured and predicted shrinkage values. The data points for the STAMP model are more closely clustered around the diagonal line, indicating that the property calibration process of the STAMP model achieves superior accuracy than the Uncorrected Residual Stress model for the tested non-fiber filled polymers.

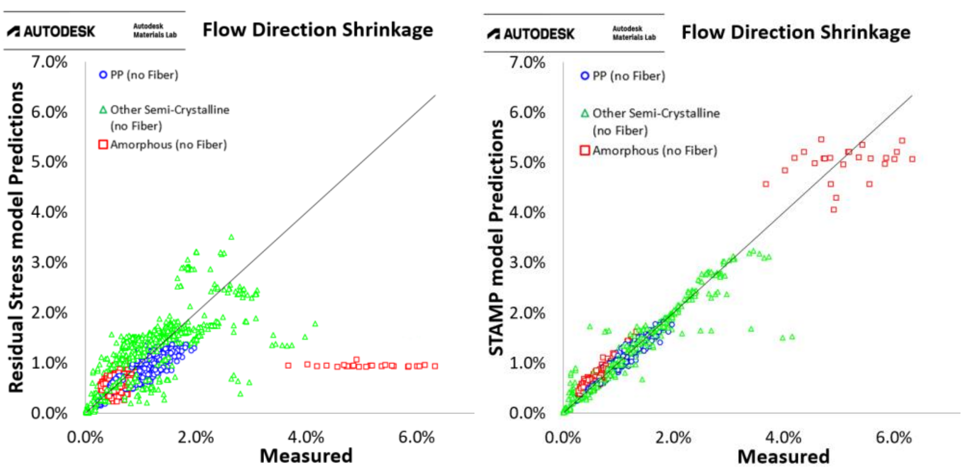


Figure 4: Flow Direction Shrinkage, comparison for 171 non-fiber filled polymers of measurement vs prediction of the Uncorrected Residual Stress (left) and STAMP (right) models

It is notable in Figure 5 that two materials show negative transverse direction measured shrinkage values. A negative shrinkage indicates that the molded sample expanded slightly in the transverse (width) direction after ejection from the mold. This can occur for soft materials, in these cases being PVC and TPU polymers. This occurs because there is a release of the strong flow direction stresses after ejection. This anisotropy of the shrinkage response is not predicted by the Uncorrected Residual Stress model, but it is predicted by the STAMP calibration model.

Figure 6 and Figure 7 show respectively the flow direction and transverse direction comparisons of measured and predicted shrinkage for 106 fiber-filled polymer compounds molded in the Autodesk Material Laboratory. Of the 106 compounds, 5 contain amorphous polymers, 30 contain polypropylenes (PP) and 71 contain other semi-crystalline polymers. 11 of the compounds contain glass fiber reinforcements longer than 1mm. The predicted shrinkage values are all from 3D analyses in the Moldflow Insight 2024 release, which used either the default Uncorrected Residual Stress shrinkage model or the STAMP (calibrated) shrinkage model. Again, the diagonal reference lines show the position of the target 1:1

correspondence between measured and predicted values. Each data point represents one of the 25 molding conditions used for each polymer. When the STAMP model is used, the data points are closely clustered around the diagonal line, demonstrating the improved accuracy of the STAMP model over the Uncorrected Residual Stress model for fiber-filled polymers.

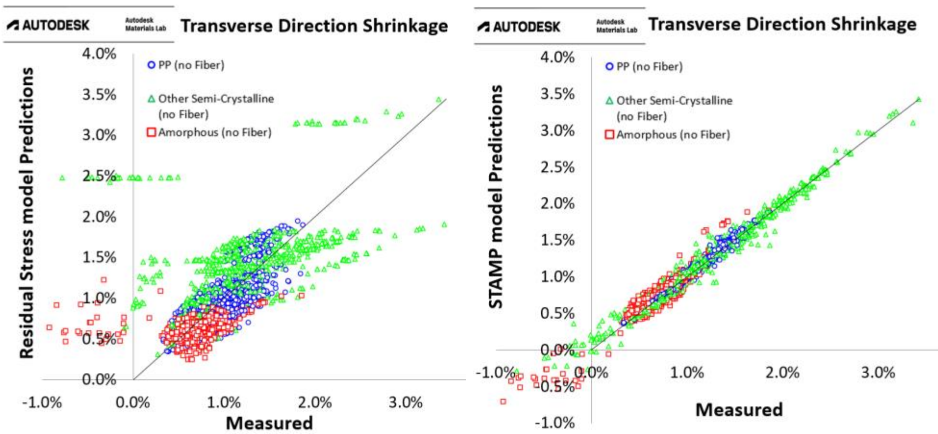


Figure 5: Transverse Direction Shrinkage, comparison for 171 non-fiber filled polymers of measurement vs prediction of the Uncorrected Residual Stress (left) and STAMP (right) models

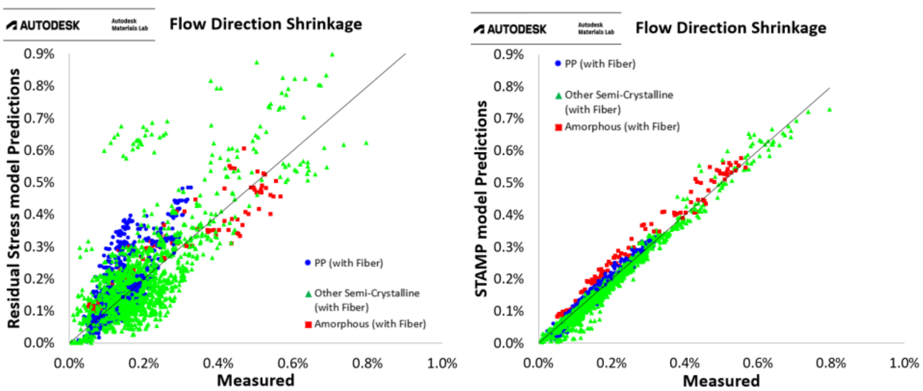


Figure 6: Flow Direction Shrinkage, comparison for 106 fiber filled polymers of measurement vs prediction of the Uncorrected Residual Stress (left) and STAMP (right) models

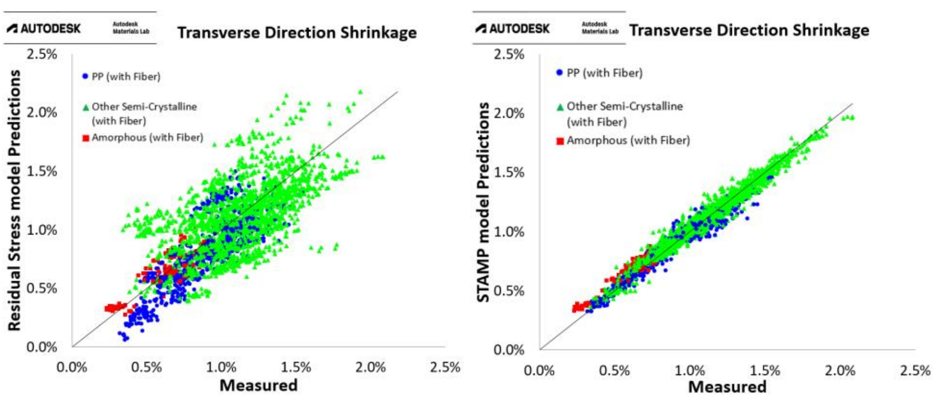


Figure 7: Transverse Direction Shrinkage, comparison for 106 fiber filled polymers of measurement vs prediction of the Uncorrected Residual Stress (left) and STAMP (right) models

Comparison of complex molding case-studies

Center-gated tray molding of PP

A validation case-study of the STAMP method was performed using a thin-walled tray geometry shown in Figure 8. This tray was molded using an unfilled PP polymer, Moplen EP301K, from LyondellBasell Australia. The molding is center gated from a cold sprue with a uniform wall section thickness of 0.8mm and overall part dimensions of 125 mm x 87 mm. The molding process included a packing phase of 30 MPa held for 5 seconds. The deflected part has a post-mold buckling saddle shape. The deflection of one corner of the molding from the plane of the other three corners was measured as 17 mm.

Figure 8: Center-gated tray molding

The Fill+Pack and Warp analyses were performed using a 3D tetrahedral mesh with 8 layers of elements through the cross-section thickness. Due to the buckling mode response, a "Large Deflection" analysis which includes geometric non-linearity of the structural solution was performed using 10-noded tetrahedral elements.

The resulting deflection predictions from the non-calibrated Residual Stress model and the STAMP method are shown in Figure 9 and Figure 10 respectively. The residual stress method incorrectly predicts a dome shape rather than the buckling shape, with a maximum deflection in the center of only 2.4 mm. The STAMP model correctly predicts the buckling shape, with a maximum deflection at one corner of 17 mm, being in close agreement with the molded part.

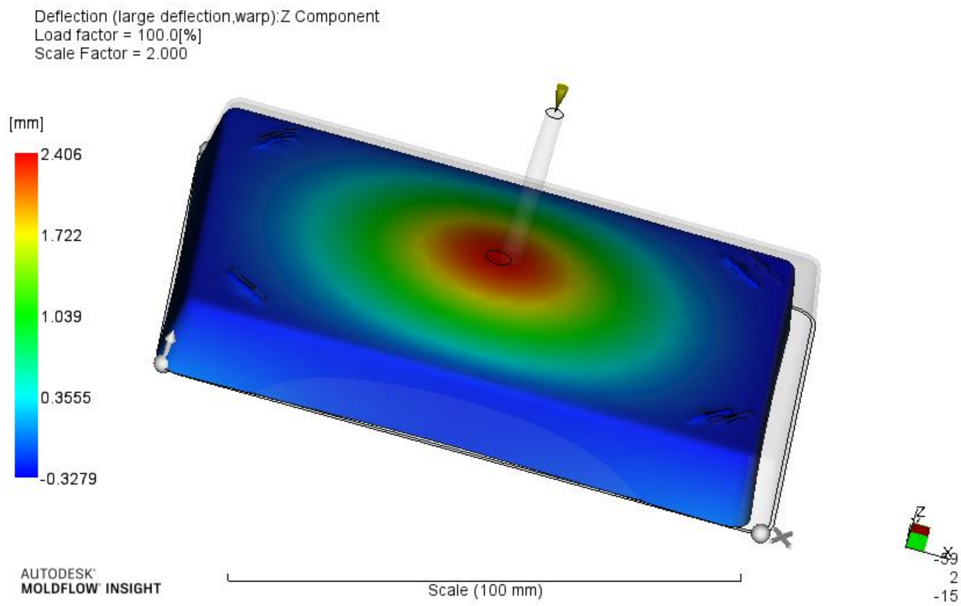


Figure 9: Residual Stress method prediction of warp shape of the tray molding

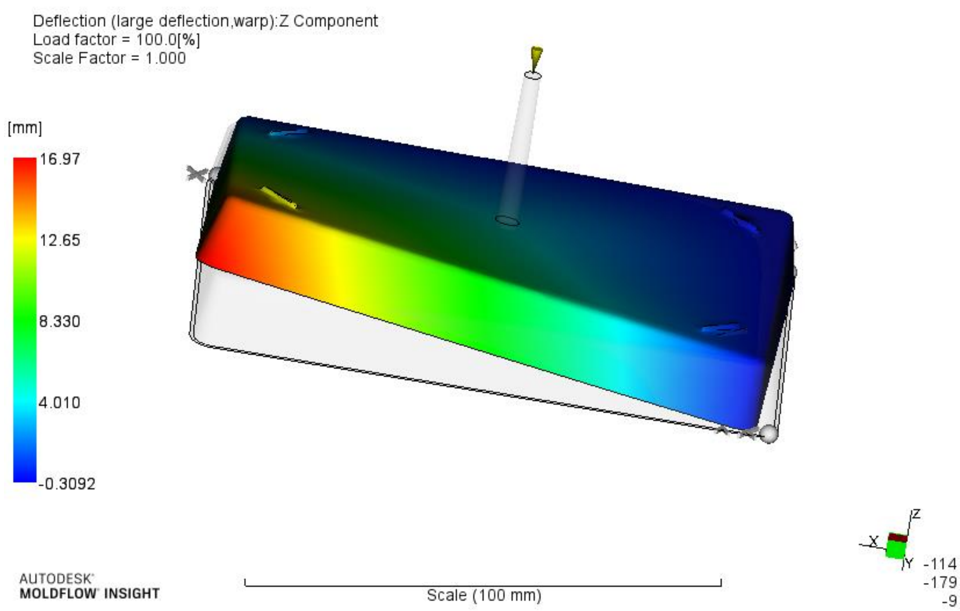


Figure 10: STAMP method prediction of warp shape of the tray molding

Conformal Cooling Box molding of Glass-Filled PA6

Validation of the improved warp prediction accuracy of the STAMP method was also performed for a Polyamide-6 (PA6) polymer compound, Ultramid B3WG6 BK00564, with 30wt% short glass fiber reinforcement from BASF Engineering Plastics. The compound was used to mold a small five-sided box (see Figure 11) with conformal cooling channels in the core to effectively cool the deep core (see Figure 12). This cooling design allowed uniform mold temperatures in the core and cavity mold halves that were varied between 80 ℃ and 95 ℃. The cavity was center gated on the under-side by a cold sprue. The cavity thickness was uniformly 2 mm, with the overall cavity dimensions being 85 mm (length), 65 mm (width) and 45 mm (height). The molding process included a packing phase of 40 MPa for 8 seconds. The maximum inwards deflection of the top lip of the box was measured in both the length and width dimensions (see Figure 13). Four mold temperature settings were used in this experiment as shown on Table 1.

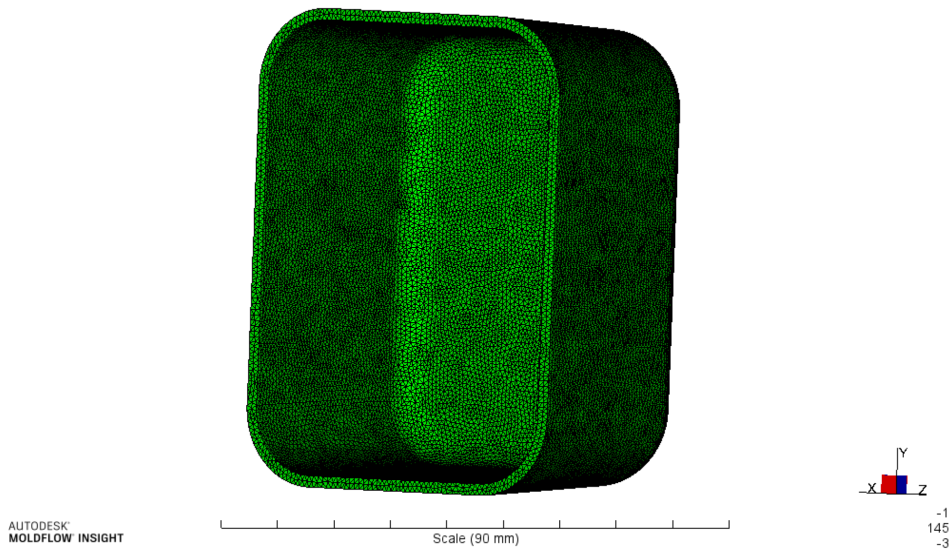


Figure 11: 3D mesh model of the Conformal Cooling Box geometry

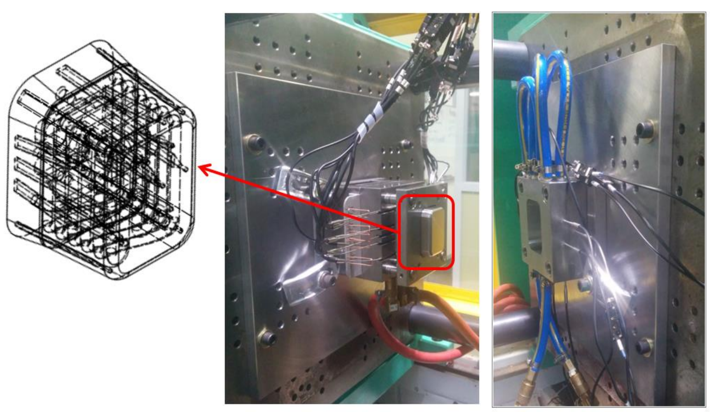


Figure 12: Cooling of the mold for the Conformal Cooling Box

Figure 13: Scheme of measurement for the Conformal Cooling Box

Molding Condition	Moving mold-half temperature, °C	Fixed mold-half temperature, °C
1	80	80
2	95	95
3	95	80
4	80	95

Table 1: Molding temperature conditions for the Conformal Cooling Box moldings

The simulation model used 12 layers of tetrahedral elements across the cross-section thickness. The calculation of part deformation was performed using 10-noded tetrahedral elements and the "Large Deflection" option which includes the effect of geometric non-linearity of the structural solution.

The measured inward deflections of the top lip of the five-sided box and the predictions from both the STAMP and Uncorrected Residual Stress methods are shown in Figure 14. Using STAMP dramatically reduces the average error of predictions from 77% to 16%.

Figure 14: Comparison of warpage predictions with experiments for the conformal cooling box

Iron frame model

The PBT part shown in Figure 15 is a historical case-study molded using Pocan T323 material from Bayer AG. The warpage was measured according to the scheme shown in Figure 16. The measured warpage is 4.5 mm. Injection molding Fill, Pack and Warp analyses were performed using 10 layers of 3D element across the thickness of the geometry. Analyses were performed using both the Uncorrected Residual Stress and STAMP shrinkage models in the Moldflow 2024 software. All simulation parameters were the default ones. The warped shape is shown in Figure 17 and the comparison of predictions with the measured deflections of molded parts is shown on Table 2 . Both simulation methods overpredicted warpage with STAMP predictions being slightly more accurate.

Experiment Measurement	Simulation Distance (mm)	Experiment Distance (mm)
Uncorrected	5.382	4.5
STAMP	5.317	4.5

Table 2: Predicted and measured warpage for the iron frame moldings

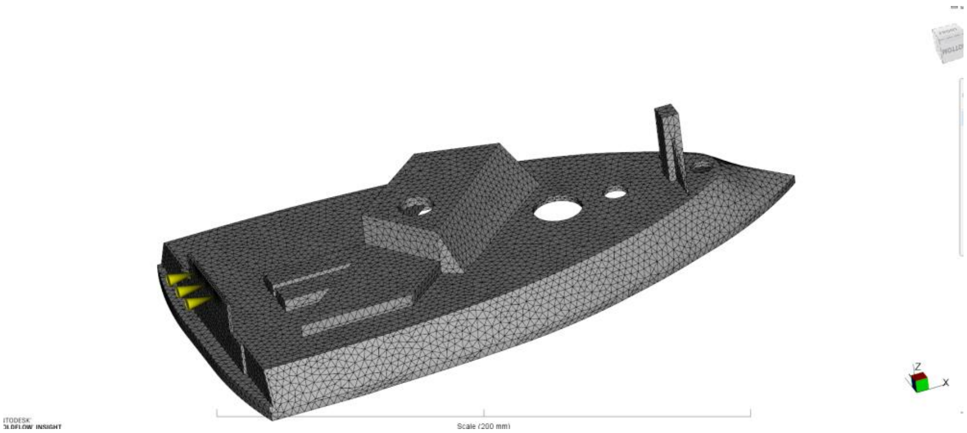


Figure 15: Mesh model of Iron frame molding

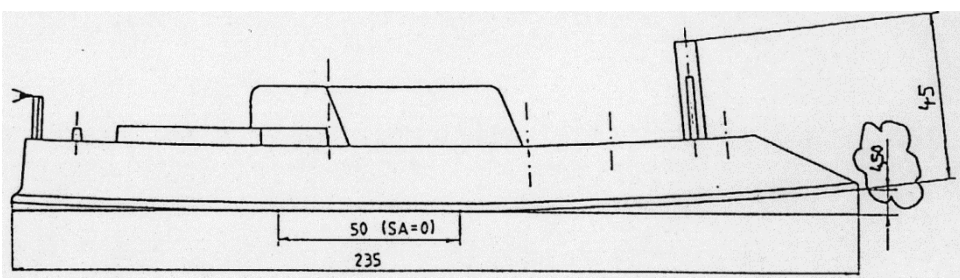
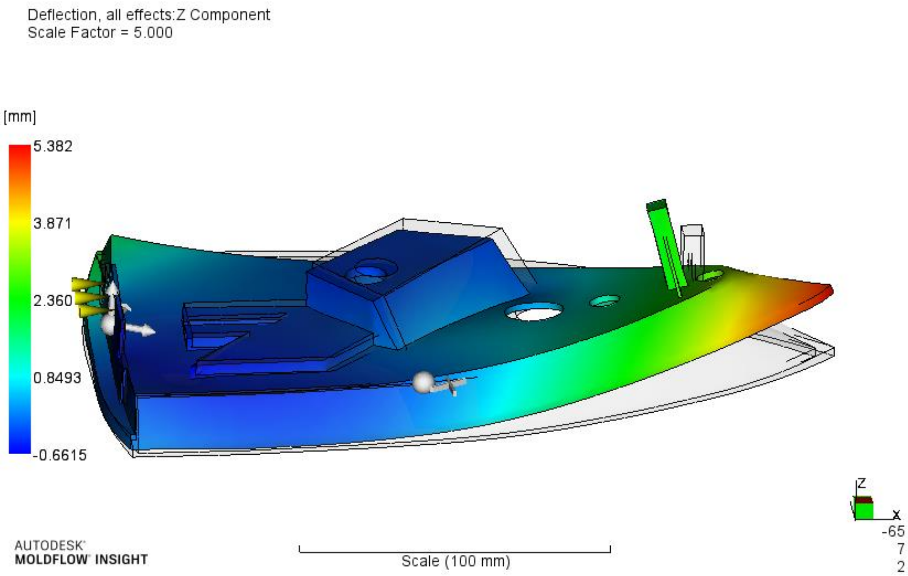
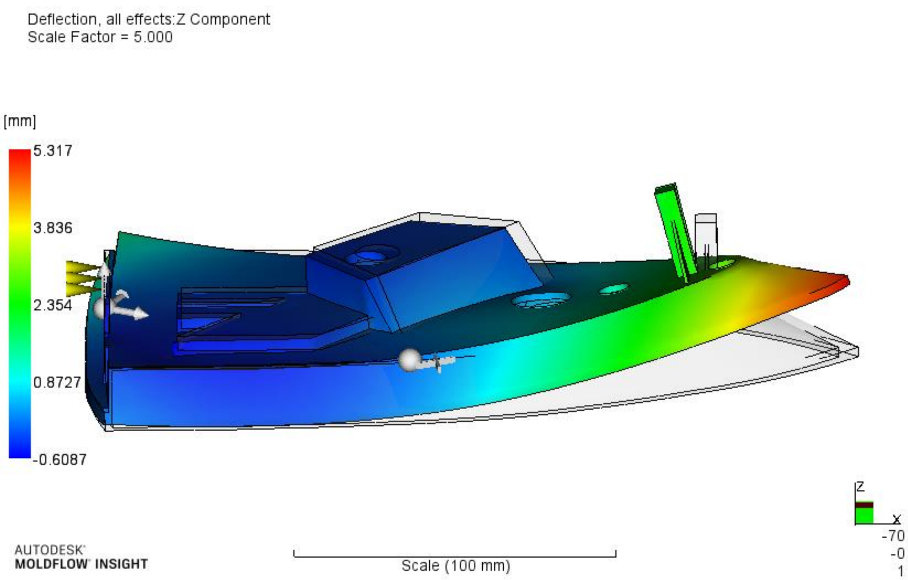


Figure 16: Scheme of warpage measurement for the iron frame moldings



a)



b)

Figure 17: Predicted warped shape of the iron frame. a) Uncorrected Residual Stress model, b) STAMP model

Warp Validation Suite

Autodesk maintains internally a suite of 20 customer molding case-studies which have measured warpage data of actual moldings, and the material is shrinkage tested. Among those 20 moldings, 17 are molded with fiber-filled thermoplastics and three are unfilled.

The measured data may be of deflection at specific locations, shrinkage between two points, difference in deflection between some locations, deviations from the round shape, etc. Some measured data are inexact, being only qualitative, e.g., “positive” or “negative”.

The warpage predictions are compared with the baseline predictions. We define the results as “better” if the average relative error of predictions decreases by more than a tolerance value, as “worse” if the average relative error of predictions increases by more than the tolerance value and as “similar” if the change is less than the tolerance value.

Warp validation tests was performed using Moldflow Insight 2024 for all three supported shrinkage models: Uncorrected Residual Stress (default), Generic Shrinkage and STAMP. Note that for comparison, analyses were also run using Moldflow Insight 2023 AMI with the Uncorrected Residual Stress model. Comparison results are shown on Table 3 in which the Moldflow Insight 2024 predictions using the Uncorrected Residual Stress model are used as the baseline.

	Compared to base line		
Build and shrinkage model	Better	Similar	Worse
2024			
Uncorrected Residual Stress	0	20	0
Generic Shrinkage	8	5	7
STAMP	6	12	2
2023			
Uncorrected Residual Stress	3	11	5

Table 3: Results of Warp Validation Test suite. The baseline for comparison is the 2024 Uncorrected Residual Stress results.

The Moldflow 2024 results with all shrinkage models show better accuracy than the Moldflow 2023 Uncorrected Residual Stress predictions. The most accurate results were obtained using the STAMP calibration model. Six cases become better with STAMP while only two become worse compared to the Moldflow 2024 Uncorrected Residual Stress results. Two of the test cases which showed improvement with STAMP now predict warpage magnitudes closely matching the measured deflections.

References

1. F.S. Costa, A. Bakharev, Z. Yuan and J. Wang, “Improved Injection Molding Warp Predictions by Characterization of Material Properties Using Measured Shrinkage Molding Data”, *SPE-ANTEC Tech. Papers* (2023).
2. P. Kennedy and R. Zheng, "High Accuracy Shrinkage and Warpage Prediction for Injection Molding", SPE-ANTEC Tech. Papers, 60 (2002).
3. Zhao, Z., and X. Jin. Property Separation Based on Inversion of Micro-Mechanics, SPE-ANTEC Tech. Papers (2001), Dallas: 560-562.
4. X. Jin, J. Wang and S. Han, "Property Calculation System for Injection Molding and Compression Molding of Fiber-Filled Polymer Composites", The 19th International Conference on Composite Materials (ICCM19), Montreal, Canada (2013)