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Research Study Demonstrates Computer Simulation Can Predict Warpage and Assist in Its Elimination

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Programs for predicting warpage in injection molded parts are relatively new. Commercial software for simulating the flow and cooling stages of injection molding have steadily gained acceptance; however, warpage software is not yet as readily accepted. This study focused on gaining an understanding of the predictive capabilities of the warpage software. The following aspects of this study were unique. (1) Quantitative results were found using a statistically designed set of experiments. (2) Comparisons between experimental and simulation results were made with parts produced in a well-instrumented and controlled injection molding machine. (3) The experimental parts were accurately measured on a coordinate measuring machine with a non-contact laser probe. (4) The effect of part geometry on warpage was investigated.

Keywords

cooling analysis, cooling time, flow analysis, injection molding, melt temperature, Moldflow, mold temperature, prediction, shrinkage, simulation, Taguchi, warpage

PROGRAMS for predicting warpage in injection-molded parts are relatively new. Commercial software for simulating the flow and cooling stages of injection molding have steadily gained acceptance; however, warpage software is not yet as readily accepted. Therefore, the Engineering Research Center for Net Shape Manufacturing (ERC) at Ohio State University, Columbus, Ohio undertook a research program to determine the effectiveness of this technology in accurately predicting warpage conditions.

A basic requirement of this research was to mold parts that would easily show warpage while remaining representative of common moldings in industry. A long, thin specimen achieves these goals. This shape produces highly directional shrinkage, which in turn produces warp. Plates and channels also form a basis for many common injection-molded parts. For these reasons, a succession of four parts were made.

A 20.32 cm long by 2.54 cm wide (8 in. long by 1 in. wide) flat plate was run first to get a baseline measurement of warpage using an uncomplicated geometry. Following the flat plate, a 20.32 cm long by 2.54 cm wide by 2.54 cm high (8 in. long by 1 in. wide by 1 in. high) channel section was molded. The third (channel with rib on the back edge) and fourth (channel with third wall) geometries show the effects of structural support on warp. Although the third wall adds stiffness to the part by increasing the moment of inertia, the way in which the wall shrinks affects the magnitude of the warp. Therefore, the third and fourth geometries illustrate the trade-off between stiffness and shrinkage.

The ERC's 75 metric ton injection molding machine was used in the experimental study. With the exception of the frames and interchangeable inserts, all tooling was designed and constructed at the ERC. A mold plate forms the flat surfaces on the core side of the parts. This plate bolts onto the core side interchangeable insert. This assembly slides into the frame on the stationary side of the machine. A heated sprue bushing slides through the frame, interchangeable insert, and mold plate and is held in place with a retaining ring.

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For this study, modified trapezoidal runners were chosen. Moldflow flow and cooling analyses were used to size the runners. Runners must be sufficiently large so that they do not freeze during filling, yet small enough that their freeze times do not unduly increase the cycle time. Several simulations were performed with MF/FLOW* flow analysis software, and it was determined that a hydraulic diameter of 0.386 cm (0.152 in.) was sufficient to fill the part without lengthening the cycle.

An edge gate was used in this study. The gate was designed using two-dimensional flow analysis. Particular attention was paid to the shear rate through the gate. Moldflow suggests a

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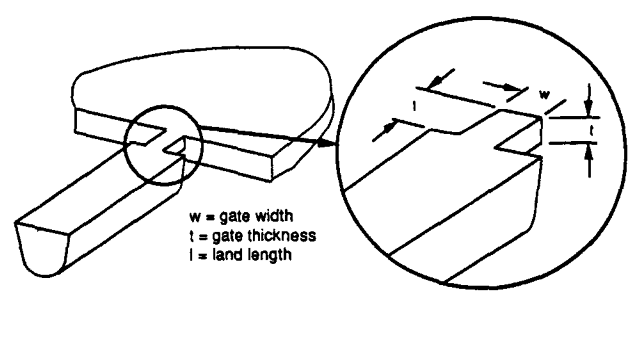

Fig. 1 Various dimensions of an edge gate

maximum shear rate of 100,000/s for polypropylene. The MF/FLOW analysis showed that a gate thickness of 0.127 cm (0.050 in.) produces shear rates well below the suggested limit. This size also allows the mold to be used with other materials, such as ABS, which have lower allowable shear rates. Figure 1 shows the various dimensions of an edge gate. The mold used in this study has a gate with 0.0762 cm land length by 0.254 cm width by 0.127 cm thickness (0.030 in. land length by 0.100 in. width by 0.050 in. thickness). This gives a hydraulic diameter of 0.169 cm (0.0667 in.).

The Taguchi method was used in designing the experiments and simulations. (The Taguchi method is a statistical method for reducing the number of experiments without a loss of information. See Barker in "Selected References.") Three levels of each variable were used. The three levels of mold and melt temperature span the range of common conditions for polypropylene. The cooling time varies from the minimum necessary to solidify the part to roughly twice this value. The packing pressure begins at a level well below the maximum pressure experienced during filling. The upper level was the maximum value before parts began to stick in the mold. The range of injection time was chosen using two-dimensional flow analyses. The lower value was chosen based on the lowest allowable end of fill temperature just above no-flow. The upper level was based on the maximum allowable shear rate. The final decision for the ranges of the above process conditions was based on test runs of the experimental mold. The wide range of experimental conditions used, therefore, went well beyond the parameters of a practical mold processing window. Although extreme conditions were used to evaluate the predictive accuracy of the software, note that the analysis programs were not designed to be run at such extremes.

All test parts were measured on a Sheffield coordinate measuring machine (CMM). A noncontact laser probe was used to ensure that the part was not deflected during measurement. A jig was constructed to ensure correct placement of the parts on the CMM.

The part rested upon three pins with four posts defining the X and Y axes. A plane was defined by measuring the Z-coordinate of the tips of the three pins. The plane was then shifted in the $-Z$ direction to account for the part thickness. Eighty-eight points were measured in a 4 by 22 grid across the part surface. The deviation from the plane described by the pins was recorded for each point.

Plots of factor effects isolated the contribution to warpage of the individual processing conditions. These effects were computed by averaging the warps for each experiment in which a factor is at a given level. For example, to find the effect of mold temperature at the first level, 200 °C (390 °F), the warp in rows 1 through 9 were averaged. This was then repeated for the second and third levels of mold temperature.

The results indicated that warpage is minimized in the first two geometries by selecting the largest values of mold and melt temperature, injection time, and cooling time. For the first geometry, warp is minimized by selecting the middle level of pack pressure, while the high level must be used for the second geometry. For both geometries, injection time contributes the most to warp with packing pressure a distant second.

The third and fourth geometries exhibit significantly different behavior. Although the mold temperature, melt temperature, and cooling time exhibit similar trends to those of the first two geometries, injection time and packing pressure differ. Packing pressure played a larger role in driving warpage while the significance of injection time was reduced. Also, the injection rate trend reversed with a lower injection time decreasing warp.

The model was meshed using triangular and beam elements. Several surfaces defined each of the three sides projecting from the base plate, thereby accounting for the thickness variation due to draft angle in the mold. For example, the ribs projecting from the base to produce the channel were made up of four surfaces each.

The following procedure was used in simulating each experiment. The Moldflow MF/FLOW was used for three-dimensional flow analysis at a specified mold temperature. A Moldflow MF/COOL cooling analysis was run using flow analysis results as input. Inputs to MF/COOL included the pack time, cooling time, cooling water inlet temperature, and cooling water flow rate. The results from the cooling simulations agreed well with the temperatures given by thermocouples in the test mold.

MF/FLOW flow and packing analysis was run for a more detailed flow analysis as well as the packing phase simulation. Cooling analysis results were used by MF/FLOW to give a more accurate mold temperature distribution. This flow and packing analysis uses a finite difference scheme to describe temperature, shear rate, and frozen layer thickness profiles. Fill patterns for each geometry correlated well with short shots of the experimental mold.

The Moldflow MF/WARP was used to compute the part shrinkage and warpage due to the injection molding process. The inputs to this software were the meshed model, Young's modulus parallel to flow, Young's modulus perpendicular to flow, and Poisson's ratio. The values of the mechanical properties were as follows: 1800 MPa (261,000 psi) for parallel Young's modulus, 1500 MPa (217,500 psi) for perpendicular Young's modulus, and 0.36 for Poisson's ratio. Moldflow offers three warpage analyses: small displacement, large displacement, and linear buckling. A linear buckling analysis was run for each experiment. Positive eigenvalues (a measurement of critical load factors) greater than one were found for each analysis, indicating stability. Therefore, buckling was not a concern.

Several test runs using large displacement analyses showed that nodal deflection occurred in a linear manner over the load steps. This indicated that the linear assumption of the small displacement analysis was sufficient. Therefore, small displacement analysis was used in each case to reduce compute time.

Both the first and second geometries warped towards the cavity side of the tooling. Cooling was reasonably uniform, and thermocouple traces in the mold and simulation results show that the cavity side is only one degree warmer than the core side throughout the cycle. This trend reversed for the third and fourth geometries. The direction of warp was always towards the cavity side, which implies that the small temperature difference did not have a major effect.

Table 1 Warpage of first and second geometries

Experiment	Part 1			Part 2		
No.	Experimental	MF	Difference	Experimental	MF	Difference
1	0.3104	0.1706	-0.1398	0.3094	0.1924	0.1170
2	0.0418	0.0362	0.0056	0.1281	0.1123	0.0158
3	0.0574	0.0501	0.0073	0.0372	0.0285	0.0087
4	0.1717	0.1432	-0.0285	0.1717	0.1497	-0.0220
5	0.1052	0.1187	0.0135	0.1246	0.1252	0.0006
6	0.0760	0.0672	-0.0088	0.0900	0.0842	0.0058
7	0.1392	0.1315	0.0077	0.1457	0.1369	-0.0088
8	0.0805	0.0642	-0.0163	0.1505	0.1332	0.0173
9	0.0703	0.0592	0.0111	0.1021	0.0915	-0.0106
10	0.1866	0.1628	-0.0238	0.2605	0.1886	-0.0719
11	0.0596	0.0654	0.0058	0.0915	0.0967	0.0052
12	0.0432	0.0335	0.0097	0.0492	0.0414	0.0078
13	0.1688	0.1436	-0.0232	0.1884	0.1546	0.0338
14	0.1200	0.1021	-0.0179	0.1745	0.1533	-0.0212
15	0.0664	0.0527	-0.0137	0.0850	0.0734	-0.0116
16	0.1801	0.1593	-0.0208	0.1645	0.1465	0.0180
17	0.1200	0.1084	0.0116	0.1145	0.0917	-0.0228
18	0.0822	0.0755	0.0067	0.0733	0.0822	0.0089
19	0.2522	0.1627	0.0895	0.2324	0.1684	-0.0640
20	0.0631	0.0518	-0.0113	0.1333	0.1226	0.0107
21	0.0606	0.0432	-0.0174	0.0396	0.0381	0.0105
22	0.1967	0.1653	-0.0314	0.2290	0.1657	0.0633
23	0.0732	0.0647	0.0085	0.1194	0.1002	0.0192
24	0.0237	0.0194	0.0043	0.0699	0.0733	0.0034
25	0.1445	0.1213	-0.0222	0.1439	0.1196	-0.0243
26	0.1048	0.0901	-0.0147	0.1083	0.1145	0.0062
27	0.0725	0.0785	0.0060	0.1176	0.1203	0.0027

As previously mentioned, 88 points were measured on each experimental part. A program was written to extract the coordinates of the corresponding nodes on the warped models from the appropriate Moldflow files. The program first extracts the nodal coordinates from the Moldflow node file. Next, the program reads the nodal deflections from the warpage output file. The deflections are added to the original nodal locations to produce the deflected coordinates of each node. These coordinates are then translated in the X and Y directions so that the same origin is used by both the CMM and the nodal coordinates. The program then extracts the coordinates of the three points corresponding to the pins on the experimental jig. These points define a base plane from which deviations are measured.

In order to study the accuracy of simulation results, warp was defined as the maximum deviation minus the minimum deviation. Table 1 compares experimental and simulation results for the first two geometries. In most cases, the simulation predictions were within 0.051 cm (0.02 in.) of experimental results, with several being within 0.0254 cm (0.01 in.). Large differences occurred for experiments that used an injection time of 0.5 s. Discussions with Moldflow suggest that this lack of correlation is likely due to elemental shrinkages occurring outside of the range of test data for the material.

Six of the twenty-seven experiments were simulated for the third and fourth geometries. For each of these two parts, the two experiments yielding the largest warp, the two with the lowest warp, and the two in between were simulated. The primary warp in the third and fourth geometries occurred as a bulge in the gate area.

Simulations were unable to replicate the gate area warp. Therefore, a comparison was made for the 22 points along the back rib of the parts. This definition yielded a more favorable comparison. The simulations predicted the warp along the back wall of part 3 to within 0.0254 cm (0.010 in.) for four of the experiments. The predictions were not as accurate for the fourth geometry, but were still within 0.0381 cm (0.015 in.) in most cases.

In the experimental study, the measured absolute value of the 88 points were averaged to define warp. This definition was applied to simulation results for the first two geometries in order to compare factor effects. With the exception of melt temperature, the trends were similar. The effect of injection time, however, was not as pronounced for the simulations. Also, cooling time showed no distinct trend.

Most previous studies in the use of simulation software for injection molding focused on the qualitative usefulness of these programs in aiding designers and manufacturers. The following aspects of this study were unique. (1) Quantitative results were found using a statistically designed set of experiments. (2) Comparisons between experimental and simulation results were made with parts produced in a well-instrumented and controlled injection molding machine. (3) The experimental parts were accurately measured on a coordinate measurement machine with a noncontact laser probe. (4) The effect of part geometry on warpage was investigated.

In many cases, computer predictions compared favorably with experimental results. The majority of simulations yielded warpage within 0.0508 cm (0.020 in.) of the experiments. The exceptions occurred for two geometries that were essentially unsupported plates under conditions of high-injection velocity. This discrepancy was likely due to shrinkages outside of the range tested by the software vendor for the material under consideration. Note that although the software was inaccurate for high shrinkages, in practice this area of extreme processing conditions would be avoided.

Simulations were unable to capture the large warp in the gate area of the third and fourth geometries. This can likely be attributed to the extreme conditions of pressure, temperature, shear rate, and shrinkage that occur near the gate. Also, the runners and gates were modeled as beam elements with an attribute diameter in order to more accurately model heat transfer. Because the hydraulic diameter was used instead of plate elements with attribute thicknesses, the geometry of the gate was not truly represented. This may have contributed to the error in the gate area warpage.

Perhaps of more use to engineers than the accurate prediction of warp is the ability to discover methods of reducing warp through changes in processing conditions. Therefore, the individual effects of the five processing conditions were isolated for the first two geometries. The trends of the factor effects compared well with experiments. The ability of the software to predict these trends should prove useful to process engineers.

Selected References

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