Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 47 (2020) 987–990

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

23rd International Conference on Material Forming (ESAFORM 2020)

Simulation of Shrinkage and Warpage of Rotationally Moulded Polymer Parts

Jitendra Seregar[a,*], Mark McCourt [a], Mark Kearns [a], Peter Martin [a], Gary Menary [a]

Polymer Processing Research Centre, School of Mechanical and Aerospace Engineering, Queen's University Belfast, Ashby Building, Stranmillis Road, Belfast, BT9 5AH, UK

* Corresponding author. Tel.: +44 2890974696. *E-mail address:* jseregar01@qub.ac.uk

Abstract

The rotomoulding industry is impeded by long manufacturing cycle times, due to insufficient time required for the materials to achieve a stable state on cooling. Thermal residual stresses are induced in rotomoulded parts due to uncontrolled heat transfer, producing shrinkage and warpage in parts. There is little information about quantifying shrinkage and warpage due to a lack of available experimental data. The main aim of this work is to develop simulation model for shrinkage and warpage occurrence in rotomoulded polymer parts. In this work, the Abaqus FE modelling tool is used for obtaining the thermal coefficients data required in shrinkage model. The simulation results obtained by cooling of the molten polymer fuel tank part has provided information about heat transfer coefficient data. It is expected that once model is developed taking into account the effect of crystallization in polymers on shrinkage, it will be used to simulate shrinkage and warpage in actual rotomoulded parts. However, in this work only preliminary results are discussed. This simulation work provides a scientific understanding needed to achieve desired optimum mould surface temperature for improved cycle time, whilst minimizing shrinkage and warpage occurrence.

Keywords: Rotational Moulding; Simulation; Shrinkage and Warpage; Rotomoulding Simulation.

1. Introduction

Rotational moulding is a simple process of manufacturing hollow thermoplastic parts in a mould that rotates around two perpendicular axes, wherein heat is supplied externally. This process includes stages like in any other plastic manufacturing method namely 1) heating of the material 2) blending and shaping the desired part and 3) cooling (solidifying) the part. It is difficult to conduct a large number of experimental trials in order to find optimum process parameters. Nevertheless, the simulation analysis provides a set of probable outcomes under different rotomoulding conditions which reduces time and money.

Many numerical models were developed from Crawford and Nugent [1] to Nguyen et al. [2] examined the fact of scientific understanding of unsteady heat transfer for the purpose of identifying optimum process variables. The Simulation results provide information about heating coefficients, cycle time, wall thickness distribution and temperature gradients.

Nomenclature

Q_{Rej}	Heat rejection
FE	Finite Element
h	Convective heat transfer coefficient

Shrinkage can be defined as an equal decrease in the volume of the part being moulded. Whereas the warpage is an unequal shrinkage of irregular shrinkage of the part. The main critical reason for shrinkage and warpage is the cooling rate of the rotomoulded part. Polymers have a tendency to shrink depending on the level of crystallization achieved in the process. Stiffness of the part wall also contributes to the deformation in the part because the vacuum force (created as a

10.1016/j.promfg.2020.04.303

result of the decrease in air volume during cooling) dominates stiffness of the part [3], [4], [7] & [6]. The problem of shrinkage could be overcome by adding tolerance to the mould dimensions during the design of the mould. However, rapid cooling can often lead to warping of the part. Thus, it is very important to have control over the cooling rate. Warpage can be classified depending upon the type of differential shrinkage, namely 1) concave, 2) convex, and 3) irregular.

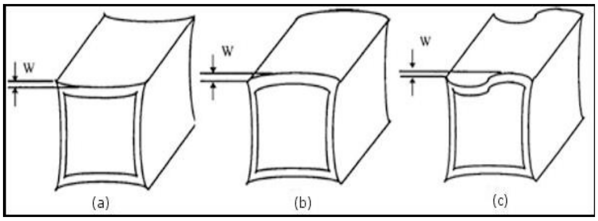

Fig. 1. Types of warpage: a) concave b) convex and c) irregular [5].

Many researchers [3], [5], [7] & [8] have carried out an experimental investigation to understand the warpage occurrence. All these works are specific to the mould they used, temperature conditions and the method to quantify the deviation of the part from design dimensions. The mould starts cooling from the external surface and the inner surface is relatively cooling very slow. The consequence of this large temperature gradient between part walls gives rise to residual stresses in the part. Residual stresses induced in part wall due to uncontrolled heat transfer producing shrinkage and warpage in the parts. The reason is being non-homogeneous cooling of polymer part initiates the gap between mould wall and part except at corner surfaces. The formation of air gap cooling is delayed furthermore because of the thermal inertia of air. As a result, the moulded part is subjected to bending stress which initiates warpage.

The cooling process nearly takes 70% of production time. Even though it could be reduced significantly by using internal air/water/mist and external water/mist spray. This process of reducing cooling time by the above method is not acceptable at the cost of final part quality. The controlled cooling rate is essential in order to exploit faster cooling and ensure part quality is not compromised. It is difficult to investigate thermal parameters through experimental work that plays a critical role in the warpage. Experimental results are limited and deeper scientific understanding of process parameters is difficult. In the available literature, no numerical model exists for simulating shrinkage and warpage. In order to develop the simulation model to predict shrinkage and warpage, it is important to establish an empirical relationship between cooling rate and shrinkage of the part. In this work the shrinkage and warpage in the rotomoulded fuel tank is studied numerically using the Abaqus CAE. Thermal coefficient data obtained from cooling molten tank part simulation provided necessary understanding required for shrinkage simulation.

2. Simulation Setup

The polymer used in the numerical study was low-density polyethylene (LDPE). The thermal and mechanical properties are given in table 1. Abaqus FE simulation tool is used for the simulation of the process. The mould is assumed to be static and the part wall has already formed. A fuel tank mould was modeled with dimensions of 500x360x360 mm and thickness of 4.5 mm as shown in figure 3.

Table 1. Thermo-mechanical properties of LDPE.

Thermo-mechanical properties	LDPE
density	934 Kg/m^3
thermal conductivity	0.33 W/m.K
elastic modulus	500 MPa
Poisson's ratio	0.46
specific heat	2640 N.m/Kg.K
thermal coefficient of expansion	120x10^{-6}/ºK

A finite element thermal model of the molten tank is generated using C3D4T-4 node thermally coupled tetrahedron element to mesh. In this study, the heat rejection from the sides of part wall surfaces is mainly due to convection (see fig. 2). Any other form of heat removal is neglected and crystallization effect on the process. The heat balance for the part wall surfaces are given by

Inner surface,

$$Q_{rej} = h_p(T_p - T_{air}) \quad (1)$$

Outer surface,

$$Q_{rej} = h_p(T_p - T_{amb}) \quad (2)$$

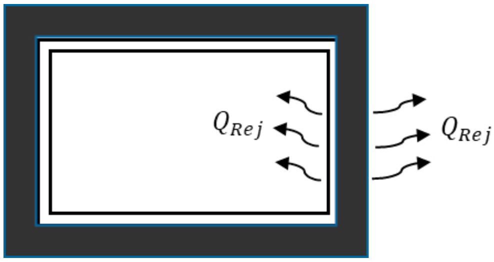

Fig. 2. Cooling of the part wall.

Since polymer characteristic is to shrink as a resultant of heat loss to the surrounding environment, a simple shrinkage model to simulate the warpage is to assume linear elastic behavior. The polymer melt behavior approximated using linear shrinkage formulation:

$$\varepsilon = \int_{T_i}^{T_f} \alpha(T_p)\, dT \quad (3)$$

Where $\alpha(T_p)$ is the linear thermal expansion coefficient (CTE) at temperature T_p. T_p is polymer temperature at a given instant of time. These strains are introduced into the polymer due to temperature gradient.

It is observed from the experimental trials that part wall near the corner edges has comparatively more material, it is more likely that it sticks to the mould even when part undergoes shrinkage. In this simulation analysis, these regions as shown in fig. 3 are restricted to move but are free to rotate.

$$U1 = U2 = U3 = 0 \quad (4)$$

Where U1, U2 & U3 are displacement in x, y and z directions. All the nodes are set to same temperature which correspond to the end of the heating stage.

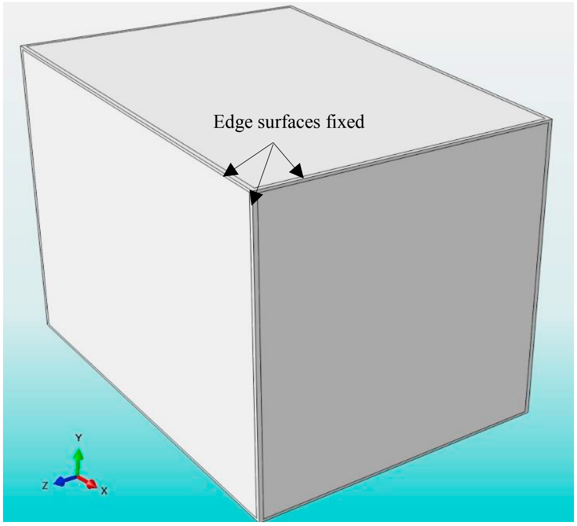

Fig. 3. Fuel tank model with edge surfaces fixed.

3. Results and Discussion

The rotationally moulded fuel tank was used for obtaining temperature data and the same are simulated using Abaqus. Figure 4 shows cooling down of the molten polymer from 245^{o}c to room temperature conditions using forced air cooling. The experimental temperature data helped in finding out the thermal coefficient values.

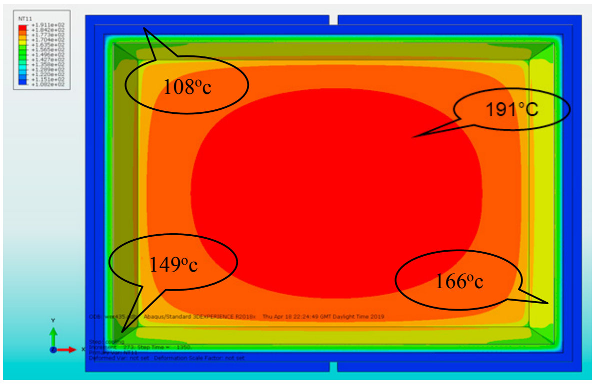

Fig. 4. C/S view of molten polymer stuck against mould wall during cooling cycle (end of 4 minutes).

The cooling stage simulation has provided empirical relationship of heat transfer coefficient value on either surfaces of the polymer part. In the current work, mould is not considered for the fact that once part wall moves away from the mould there is creation of air gap between them. Information about thermal conductivity of this gap has to be determined or approximated. In this simulation study, part is assumed to be freely hanging out in the space.

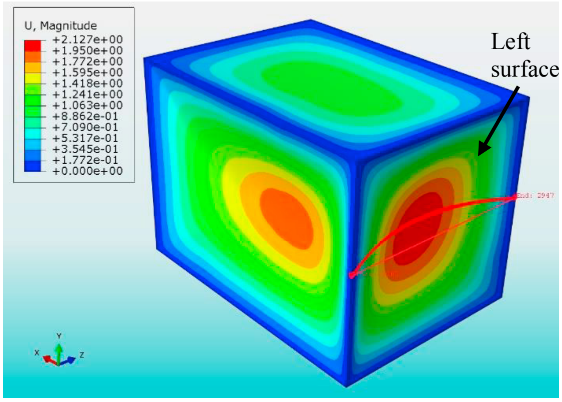

Fig. 5. Warping of the part wall due to rapid external cooling.

Two cases of air cooling scenarios are considered for warpage simulation: a) external cooling dominating internal cooling and b) internal cooling dominating external cooling. It is acceptable among researchers [9-11] that warpage is produced due to residual stresses and these thermally induced residual stresses are introduced into the part mainly by transient temperature gradient. Figures 5 & 6 shows warping of the fuel tank part for the case of dominant external cooling. One of the important observation is that left section of the part wall bend or deform more as compared to other sections of the part surface. The results shown in figure 6 & 7 are magnitude of displacement of the surface nodes from its initial position on left surfaces for respective above cases.

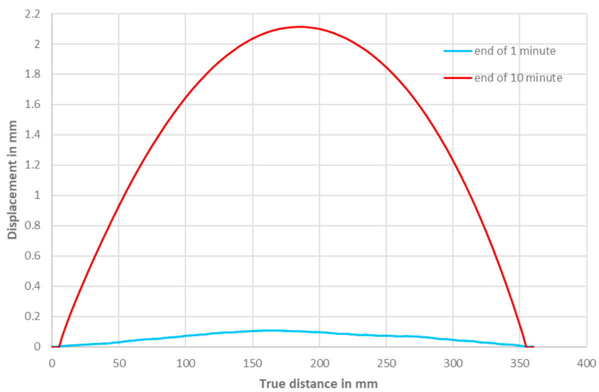

Fig. 6. Nodal displacement values along the horizontal direction (rapid external cooling.

Both the cases are shown here are after 10 minutes of cooling. Increasing cooling rate increases higher temperature gradient thus, inducing larger residual stresses in the part wall thickness. Internal cooling is found to decrease cooling time required as suggested by Tan *et al.* [12] but quality of the part found to be poor. Figures 7 & 8 shows warpage in the part for the case of internal cooling of the part.

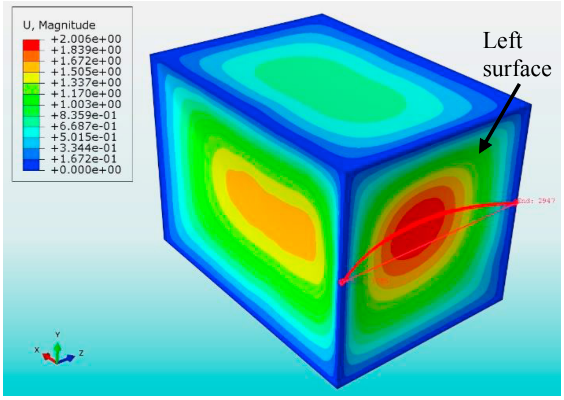

Fig. 7. Warping of the part wall due to rapid internal cooling.

Since air inside mould is cooling at faster rate than ambient air surrounding mould, vacuum force is created at the core of mould. This negative pressure is resulting in pulling action of part wall towards center of the mould. The magnitude of heat transfer coefficient values in case of (a) is order of 10:1 and vice versa in case of (b). The magnitude of warpage in case of rapid external cooling is higher than that of rapid internal cooling. The graphs in figures 6 & 8 suggest displacement of 2.127 mm from its initial position and 2.006 mm in case of external and internal cooling respectively.

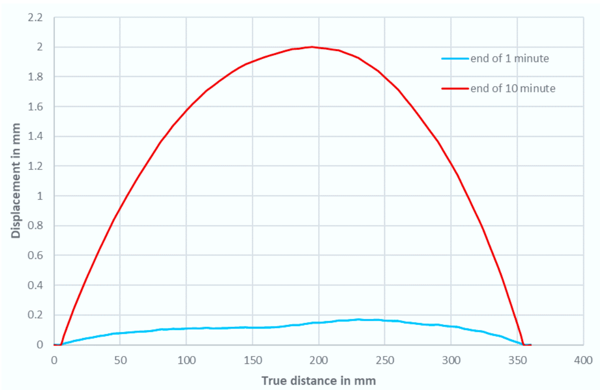

Fig. 8. Nodal displacement values along the horizontal direction (rapid internal cooling).

The useful information obtained about thermal coefficient data helps in determining the rotomoulder by approximations of possible consequences of cooling rate on the final quality of the part. Mould design also can be greatly benefitted by using these simulation data to optimize the design.

The rapid cooling is necessary for the wide application of rotational moulding. However, imbalanced cooling rate leads to residual stresses and thus, causing warpage in the part. A balanced rapid cooling method could avoid large temperature gradient through the thickness of the part and hence the warpage.

4. Conclusions

The simulation results showed a large temperature gradient through the thickness of the part is the reason for warpage occurrence in rotationally moulded parts. Two different scenarios of warpage formation are studied and the differences in the magnitude of deformation are observed. This is the first kind of attempt made to predict shrinkage and warpage by simulation analysis and needs further study. The flat surfaces are more likely to deform in contrast to the near edge surfaces and corners. The temperature gradient across surfaces of the part wall induces residual stresses which is the cause of shrinkage and warpage. Rapid external cooling is observed to produce more warpage in the part wall thickness in comparison to the rapid internal cooling method.

Shrinkage in polymers is also contributed by the level of crystallinity along with temperature gradient in the material. The model is in the early stages of analysis and needs further work. In future correspondence, the effect of crystallization in polymers on warpage will be studied and results are going to be communicated. Simulation results are not complete unless validated by test trials. So, experimental data will be used to validate simulation analysis results.

Acknowledgements

The authors acknowledge and thankful to Special EU Programmes Body (SEUPB) for the financial support provided under EU INTERREG VA programme. Special thanks are also due to Dr Ed Wright of RotoSim ltd. for valuable discussions and suggestions.

References

[1] Crawford RJ, Nugent PJ. Computer simulation of the rotational moulding process for plastics. Plast Rubber Process Appl 1989;11(2):107–124.
[2] Nguyen HT, Cosson B, Lacrampe MF, Krawczak P. Numerical simulation on the flow and heat transfer of polymer powder in rotational molding. Int J Mater Form 2015;8(3):423–438.
[3] Costa L, Cramez MC, Pontes AJ. A study on shrinkage and warpage of rotational moulded polyethylene. Mater Sci Forum 2013;957–962.
[4] Liu SJ, Ho CY. Factors affecting the warpage of rotationally moulded parts. Adv Polym Technol 1999;18(3):201–207.
[5] Liu SJ, Ho CY. An experimental investigation of the warpages in rotationally molded parts. J Reinf Plast Compos 2000;19(12):992–1002.
[6] Bhabha H, A new generation of high stiffness rotational moulding materials. Ph.D. Thesis at The Manchester Metropolitan University, 2015.
[7] Bawiskar S, White JL. Comparative study of warpage, global shrinkage, residual stresses, and mechanical behavior of rotationally molded parts produced from different polymers. Polym Eng Sci 1994;34:815–820.
[8] Iwakura K, Ohta Y, Chen CH, White JL. A basic study of warpage and heat transfer in rotational molding. ANTEC 1989:558–562.
[9] Isayev AI, Crouthamel DL. Polym Plast Technol Eng 1984;22:177.
[10] Struik LCE. Polym Eng Sci 1978;18:798.
[11] Joye DD. Journal of Appl Polym Sci 1993;47:345.
[12] Tan SB, Hornsby PR, McAfee MB, Kearns MP, McCourt MP. Internal cooling in rotational molding -A Review. Polym Eng Sci 2011;51:1683–1692.