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Experimental and Numerical Modeling the Effect of the Residual Stress in the Case of the Molding of a Plastic Part

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Abstract. *There is always time and energy optimization and reduction of faults the aim of research and in this context our article presents a study of a practical case of the deformation of a plastic part placed in a refrigerator for food storage, and that the use increases in number of these types of metals, are found in several sectors, and because of their industrial performance, a minimum residence time of the part in the mold is sought in order to reduce the cycle time of the process at the same time that the injection process is quite complex and requires a certain number of recurring questions to succeed. In the desired model. These are linked to residual stresses and deformations, pressure, mold temperature, filling threshold, shape of the part, but also to other mechanical and optical properties. Several investigations have been carried out and according to the authors the causes of these failures vary according to the manufacturing technique used. In this article, we try to find the origin of a deformation detected on a part at the end of the mold. Our work consists first of all in presenting, according to different studies, the thermomechanical properties of the material injected at different stages of the injection process. In a second step, compare the theoretical and analytical results. At the end of our study, we propose an optimization of the parameters necessary for the success of the molding and of the geometry of the assembly (mold and part).*

Keywords*: plastic injection; deformation; residual stress; heat shrinkage; thermal contact; heterogeneous cooling; simulation*

1.Introduction

Injection molding is a major component of the plastics industry, consuming a large part of the total amount of material [1]. In industrial design and manufacture, it is always difficult to make a good compromise between the most desirable shape of the parts, the cost of tooling, their weight, and strength and rigidity [2]. Time is important in the overall molding process as it represents approximately half the time of the overall production cycle [3]. If the pressure disappears, the part can lose contact with the walls of the mold in some places and can be slipped [4,5]. The heterogeneity of the thermomechanical history of the injected material generates residual stresses within the part. A combined analysis of the process and the materials can explain the mechanism. Our study focused on understanding these phenomena through the measurement and modeling of stresses and strains in injected thermoplastic parts: during the plastic and elastic deformation of metal, the mechanical energy produced is partially converted into heat while the rest is stored. strain energy and becomes more important in the case of plastics. [6- 9]. This stored energy remains in the material after loading in the form of internal defects, phase changes and other permanent micro-structural changes [10]. The residual stresses inside the parts at the exit of the mold can have two origins: The shear stresses resulting from the flow during filling and compacting does not completely relax at the time of solidification due to the viscoelastic character of the material and normal stresses, which are due to the confinement of the polymer in the cavity linked to the pressure, to the objective, to the fixed stresses induced by the flow. Their effect on molecular orientation, on crystallization, is first-order [11]. They induce anisotropy and heterogeneity of rheological behavior in the solid state and shrinkage [12]. However, it is accepted that their amplitude is

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smaller than the other sources of constraints [13, 14] and is neglected in the great majority of current models. On the other hand, frozen pressure is essential [15,16], the mechanisms have shown. During the injection cycle, the different layers solidify at very different pressure levels. When the part comes out of the mold, it undergoes an expansion linked to the return to atmospheric pressure, which is different from one layer to another. The layers being integral, there will be an average expansion and tensile or compressive stresses will appear in the thickness of the part.

2. Materials and methods

2.1. Theoretical method

The molding process begins by injecting the molten polymer into a relatively cool mold cavity. The polymer undergoes temperature degradation and finally becomes increasingly rigid in order to be able to be ejected from the tool. After ejection, the part cools to room temperature. The energy requirements for processing are determined by the efficiency of the molding machines and the plastic processing requirements. Processing conditions such as drying temperature, melting temperature, and mold temperature contribute to overall energy requirements, to the energy, Q, needed to bring a polymer to room temperature, Ts, of processing (melting) at the temperature, Tf, is given by [17]:

$$Q = m.Cp(T_f - T_s)$$

m is the mass of the polymer and Cp is the specific heat of the polymer at constant pressure.

In general, the models developed to predict the stress residues or the defects of plastic parts assumed to be a linear thermoelastic behaviour in which the of momentum and energy equations are similar to those presented in ‘‘ Flow-induced stresses models ’’ Section with the Cauchy stress tensor, commonly decomposed into a hydrostatic part p, and a deviatoric part σ^d is determined by [18],

$$\sigma = pI + \sigma^d \qquad (1)$$

where I is the identity tensor,

$$p = \int_0^t (\frac{\alpha}{k} - \frac{i}{k} trD) ds \qquad (2)$$

$$\sigma^d = 2\int_0^t G\big(\varepsilon(t), \varepsilon(s)\big) D(s) ds \qquad (3)$$

and

$$\varepsilon(t) = \int_0^t \frac{1}{aT}\, ds \qquad (4)$$

where α is the coefficient of thermal expansion, k the coefficient of compressibility, G(t,s) is the shear relaxation modulus , ε is the reduced time, and a_T is the shift factor of the time–temperature superposition principle.

For the free or unconstrained quenching, σ . n = 0 [19].

It’s associated with heterogeneous cooling also leads to residual stresses called thermal stresses. To approach the conditions experienced by a polymer leaving an extrusion die, out of calibration we first consider the effects of shrinkage free quenching, that is to say without considering that metal walls can hinder this withdrawal. Suppose that below a solidification temperature Ts, the polymer behaves like an elastic solid, with a modulus E and a Poisson's ratio ν, and above, like a liquid, which does not hinder the shrinkage [20].

Suppose that below a solidification temperature T_s, the polymer behaves like elastic solid, with a modulus and a Poisson's ratio ν, and above, as a liquid which does not interfere with the shrinkage [21]. On cooling, there is first progression of a solidification front, then the polymer reaches room temperature T_f without phase change. Consider a flat plate initially at the temperature T_0. A first layer solidifies on the surface, while being free to perform its thermal shrinkage. The associated deformation is α (T_s - T_f), where α is the linear expansion coefficient. On the other hand, the more interior layers which will solidify later, will be subjected to the same deformation α (T_s -T_f), but they will see their withdrawal blocked by the external layers. They will find themselves in traction, and put the outer layers in compression. The thermo elastic law for T <T_s, knowing a temperature (Tres), it can calculate the distribution of residual stresses σres (z) by the equation

$$\sigma res = \frac{E_\infty}{1-v}\alpha\left[\overline{T_{res}} - T_{res}\,(Z)\right] \tag{5}$$

whereE_∞ is the long-term modulus, v is the Poisson ratio, α is the thermal expansion coefficient, and $\overline{T_{res}}$ is the average value of Tres through the specimen thickness

We obtain the value of the stress at any instant t and dimension z in the thickness [11]:

$$\sigma_{xx}(z,t) = \frac{\alpha E}{1-v}\left[T_s - T(z,t) + \int_{t_s(z)}^{t} \frac{1}{h - h_s(\tau)}\left(\int_{h_s(\tau)}^{h} \frac{dT}{dt}(\zeta,\tau)d\zeta\right)d\tau\right] \tag{6}$$

In the previous equation, we have integrated over time between t_s (z), instant when the solidification front reaches the z side, and the current instant t, and we integrated in the thickness in the solidified zone at moment t, included between $h_s(\tau)$, which is the position of the solidification front at the instant τ, and h.

Two semi-infinite medium are initially considered at two different uniform temperatures T_{i1} and T_{i2}.At the initial moment, the two media are placed in contact and the temperature evolution within the two media is investigated.

$$T_c = \frac{E_1 T_{i1} + E_2 T_{i2}}{E_1 + E_2} \tag{7}$$

Note that the contact temperature between the two media remains constant throughout the heat transfer. It is the medium that has the greatest thermal effusivity that imposes the temperature of contact. Thermal contact In the event of loss of contact with the wall, the space thus created will significantly modify the thermal exchange conditions between the cold walls of the mold and the partially solidified polymer in the cavity [22]. A recent study [23] shows this very clearly: as soon as the pressure in the cavity becomes zero, there is a sudden increase in the thermal resistance of contact between the work piece and the imprint, testifying so significant formation of an air gap at the interface piece / mold. It is therefore clear that the heat from the center of the polymer can no longer be properly removed (by conduction) by the cold walls of the mold. The authors measure a temperature difference of nearly 20°C between the polymer and the mold [23]. The consequences on the kinetics, but especially on the cooling symmetry and therefore on the constraints can be very important. The piece is denser to the heart than the skin [11]. The heterogeneity of the mechanical or shrinkage properties in a material can be a source, alone, of residual stresses. Consider, for example, the case of a bimetallic material with two layers having different coefficients of expansion. Under the effect of a rise in temperature, each layer will deform differently. As they are indissociable, bimetallic will be the seat of constraints that will lead to its curvature. Many authors show that the mechanical and thermal properties can vary significantly in the thickness of the room. This is the case for semi-crystalline polymers [24-26] but also for amorphous polymers even if to a lesser extent [27]. It is shown, in particular, that the elastic zone of the tensile test and the elongation at break have a maximum close to the surface, that the plasticity threshold increases from the surface towards the center or that the modulus of 'Young is changing in thickness [15,28-30].

2.2. Experimental model

Validation of models and hypotheses requires a good knowledge of the conditions and experimental techniques for measuring deformations and temperatures [31].

Figure 1. Shows the part under study with the deformation detected at the outlet of the mold and after cooling

At the end of the cooling phase, we measured the interface temperatures of the part with a complex geometry with thick areas located in the corners. Figure 1-2 shows the measurement zones and temperatures of each part of the room:

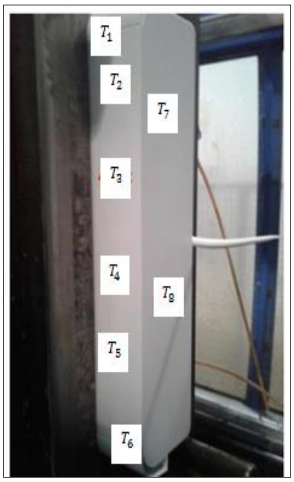

Figure 2. Temperature measurement at the interface of the part (piece at the outlet of the mold)

The measured temperature values are non-uniform across all areas of the room. The theoretical and experimental temperatures are then compared. It can be seen that the part has a measured temperature which is different from the calculated theoretical one. These results lead us to the existence of a problem of shrinkage and consequently a heterogeneous cooling of the piece which confirms the results approved in the analytical part above.

After having evoked the mathematical equations of different states of matter during the injection phase, and the comparison between theory and experimental temperature at the interface of the piece, we now move on to the numerical method to clarify the causes of this deformation and to improve the parameters influencing it.

2.3. Numerical model

For the molding and the fingerprints the mechanical and thermal characteristics of the material are defined.

The mechanical and thermal characteristics of high impact polystyrene (HIPS) and 40CMD8 steel are given in Tables 1.

Table 1. Mechanical and thermal characteristics of high impact polystyrene (HIPS) and 40CMD8 steel

Properties	High impact polystyrene	40CMD8 steel	Unit
Young's module	1900	205000	MPa
Thermal conductivity k	0.0003	0.034	W/mm.°C
Coefficient of Thermal Expansion	8E-005	1.24E-005	
Density q	1.04E-009	0.00785	T/mm^3
Poisson module P	0.41	0.3	
Specific heat Cp	0.0014	0.00046	mJ/T. °C

We define the necessary loadings:

- a temperature of 245°C on the part to be molded.
- a temperature of 40°C on the fingerprints (mobile and fixed).

3. Result and discussions

The simulation results such as stress fields, displacement, and temperature are well illustrated below.

The distribution of the stresses along the direction xx in the deformation zone is given by the image below. The curve given in Figure 3 represents the stress field along the axis xx as a function of the distance (d) to the trajectory created horizontally at the deformation zone.

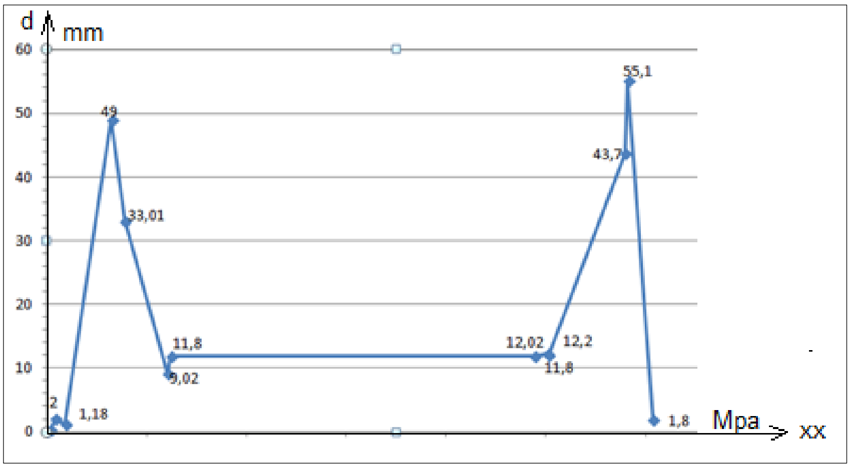

Figure 3. Evolution of the stress along the xx axis as a function of distance

This distribution presents two symmetrical essential peaks, and it can be observed that the most stressed zones are localized in the extremities of the part precisely in the thick zones with the maximum values of the stresses around 25 MPa. It can be concluded that the important values of the constraints at the ends have an influence on the final quality of our part.The result of the simulation gives a variation in the displacement along the zz axis, at the level of the deformation zone (Figure 5), this variation was detected experimentally.

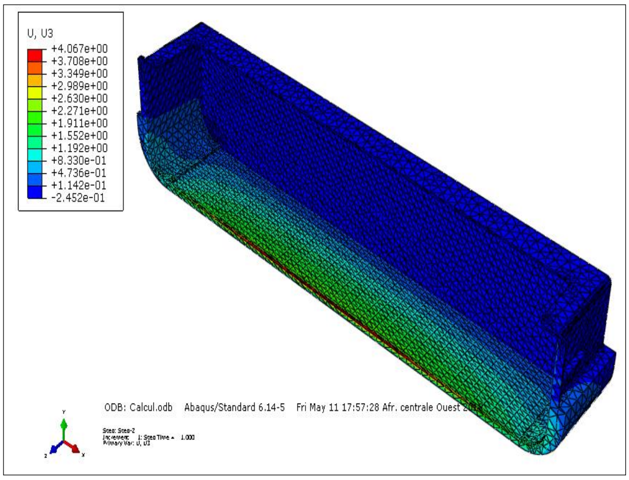

Figure 4. The displacement along the zz axis

The curve below represents the displacement along the zz axis as a function of distance to the trajectory created perpendicularly to the deformation zone.

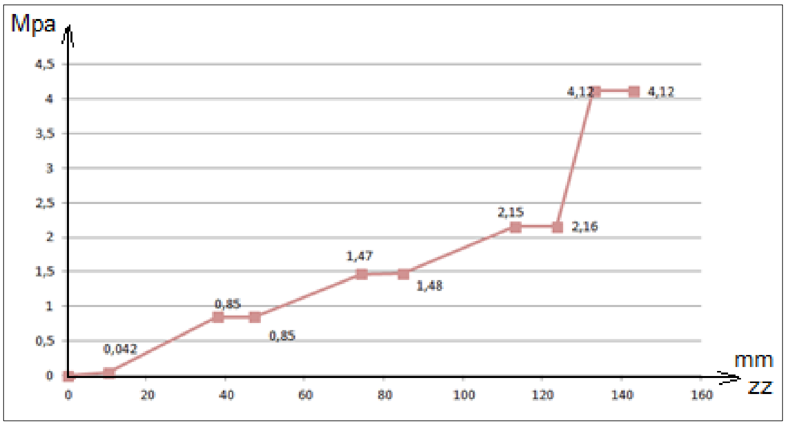

Figure 5. Evolution of displacement following zz according to distance

This displacement is greater near the edge of the piece with a value that tends to 4.067 mm. This represents the risk of deformation of the part permanently possibly due to the disturbance of localized stresses at the ends. The figures below show the flow of molten polymer into the mold during the filling phase (Figure 6).

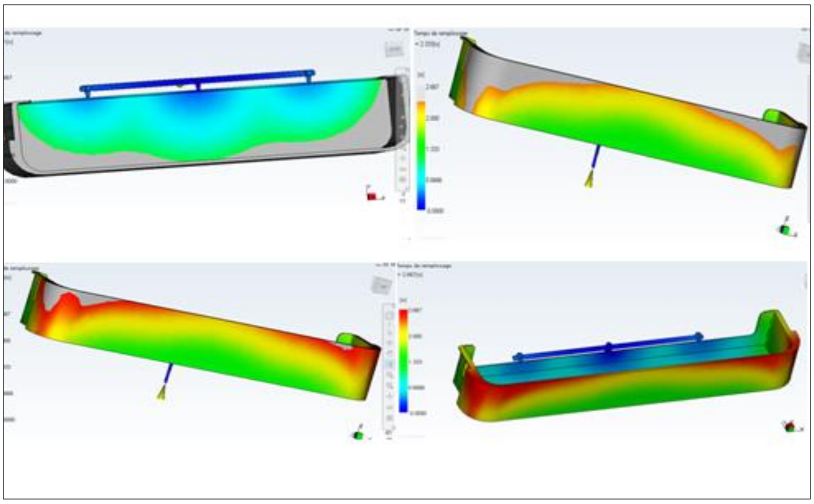

Figure 6. Flow of molten polymer into the mold

It can be noted over time that the flow is not uniform in the same areas of the mold. A difficulty in the flow of the material in the ends of the mold can be observed at the end of the filling (the distribution of red color in these areas). The variation of the temperature distribution in the mold at the end of the filling phase is very important in the areas closest to the injection thresholds. It can also be noted that the distribution of the temperature is not uniform in the deformation zone. That is, the cooling is heterogeneous during the solidification phase with the imposed time (20s) so there are thick areas that need some extra time to cool. The previous results imply that the part shrinks non-uniformly in all directions. It can be seen in Figure 11 that the shrinkage is concentrated at the ends of the piece (the thick sections) with a percentage equal to 7.5.

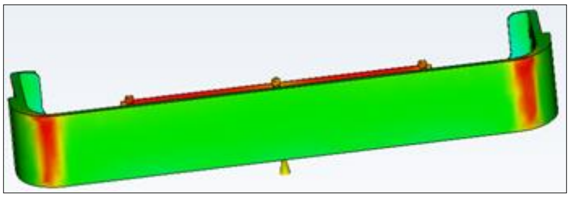

Figure 7. Result of removal in the room

Figure 8 presents a comparison between the numerical and experimental study, on the right the real room and on the left the one designed by the simulation software.

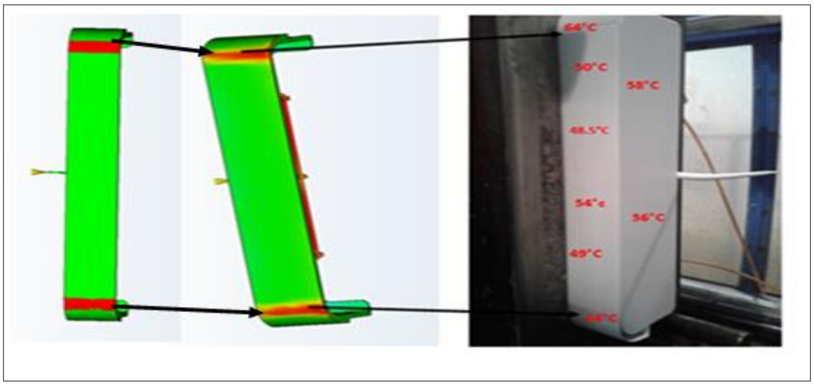

Figure 8. Comparison between numerical and experimental study

This figure shows a concordance between experimental and numerical study. A fault can be observed (a heterogeneous temperature is involved in the anisotropy of the samples) in the same zones, either in the simulation, or in the temperature measurement test at the end of the cooling phase. This defect is therefore the basis for the appearance of the deformation detected on the part. The interpretation of this phenomenon is explained by the heterogeneity of the indentations which is the major cause of the deformation of the angle in the wedge for thermoplastic materials, this phenomenon is called “front spring effect [32, 33]. Injection and mold temperatures (200°C and 30°C) have been changed. It can be noted that there is a decrease in shrinkage of about 1.5% (Figure 9).

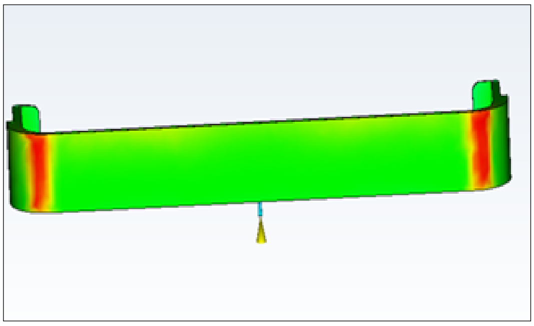

Figure 9. Result of the withdrawal after a change in temperature

In the first simulation with the actual parameters and geometry, it was noticed that there is a difficulty of the flow of the material in the ends of the mold at the end of the filling with a shrinkage of 7.5% (Figure 9) So to improve this defect, we will simulate with a modified geometry of the injection core (increase the spacing between two thresholds with 20 mm) and also reduce the injection and mold temperatures. The results are shown in Table 2.

Table 2. Results of the withdrawal simulation

Temperatures	shrinkage
Tinj=240°C Tmoule=30°C	7.2%
Tinj=225°C Tmoule=30°C	6.72%
Tinj=210°C Tmoule=30°C	6.2%
Tinj=200°C Tmoule=30°C	6.017%

Figure 10 gives an overview of the flow of molten polymer into the mold during the filling phase

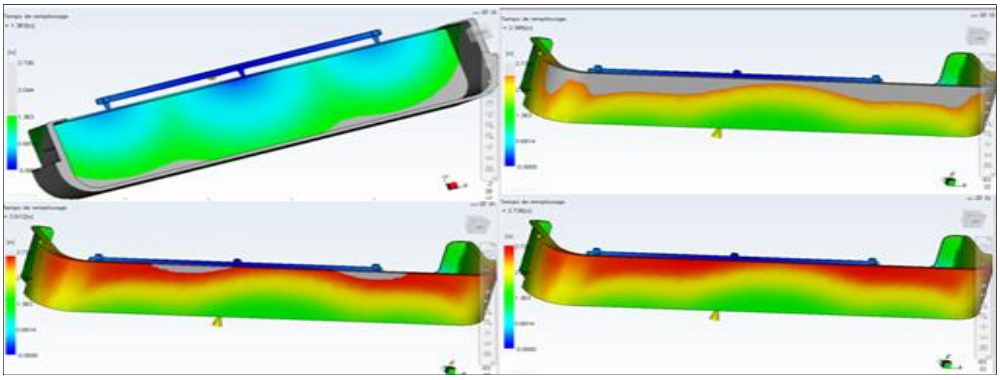

Figure 10. Flow of molten polymer into the mold

There is an improvement in the flow compared to the first simulation: the filling of the polymer is uniform in the same areas of the mold. The difficulty of the flow problem at the ends of the part (thick sections) has been eliminated. Figure 11 shows the shrinkage percentages from the last simulation:

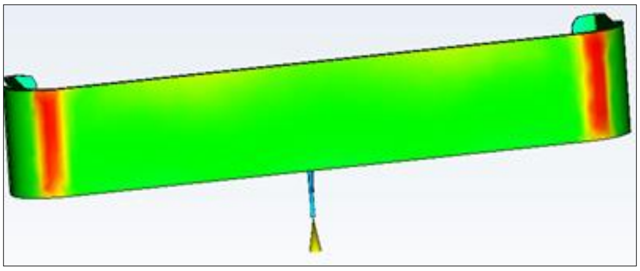

Figure 11. Flow of molten polymer into the mold

The output quantities obtained at the end of these simulations and by comparison with the experimental results as well as with research in this field [34] explain that the variations of the stresses remain more or less intense in the zones presenting geometric complications. (1.8Mpa) Figures 4 and 5, temperatures also which have non-linear cooling rates, so the shrinkages will be different (Table 2) and will result from residual stresses in several parts of the part to be studied. The results obtained previously highlight a strategy that can give the lowest shrinkage:

- Reduce the injection temperature.
- Reduce the temperature of the mold.
- Locally reduce the thickness of the part.
- Increase the spacing between the injection thresholds.
- Add additional cooling channels and / or use cooler coolant in this area.

4.Conclusions

This study remains a part of the modeling and obtaining the optimal solution for a deformation detected on a part designed by plastic molding. It emphasizes the important role of the numerical model for determining the mechanical and thermal behavior of the part during injection molding and for optimizing the necessary parameters and the geometry of the assembly (mold and part). The simulation of the compaction phase, or more generally of the compressible flows, tends, _like that of the filling_ to become a reliable design assistance tool and widely used by the mold designers and the material transformers to locate and size the injection thresholds, optimize the position of the cooling channels. The particularly complex physics of the phenomena involved is still difficult to incorporate. The software is sophisticated, but of course the accuracy of their results depends closely on the quality of the models and physical data that are not all easy to measure. Our study focused on the understanding of these phenomena through the measurement and modeling of stresses and deformations in thermoplastic injected parts. The main conclusions of each of these studies are presented in the following two paragraphs:

- Thermal conditioning conditions all phases. It is coupled with the eventual crystallization. The models can be refined to better take into account the specificities of the material (for example in the case of reinforced polymers) and the process (contact thermal resistance at the polymer-mold interface).

- For the calculation of the stresses and residual deformations, it will be necessary to improve the laws of behavior viscoelastic, in particular at the level of the principle of time-temperature superposition particularly complex for the semi crystalline polymers, but also by the taking into account of the structural heterogeneity, related to molecular orientation and / or crystallization. Moreover, it is likely that thin-film approaches are limited, even with geometries that seem to lead themselves to it (corner problem).

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