Foam Injection and Molding:

Understanding and Analyzing with Rheology Software

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Abstract: PU foams are widely used in several industry sectors including automotive, household appliances and leisure. The REM3D® software allows to simulate the injection molding process and to check the influence of the processing conditions. This article first presents the contribution of simulation for foam injection processes and then details the innovative features of the software developed to meet the industrial requirements of the process. As material data are essential, we then describe a methodology for the characterization of PU foams. On the basis of experimentally measured physical and thermo-kinetic properties, a numerical method of automatic optimization makes it possible to obtain the parameters of the material. Operated by the simulation software, these data conform to the actual formulations make it possible to increase the quality of the results. In conclusion, several examples illustrate the contribution of the simulation to industrial parts and show the extent of the results among which the density of foam in each zone of the piece; an essential indicator to estimate the parts quality and their performance.

Keywords: polyurethane foam, simulation, rheology, expansion injection, adaptive remeshing

1. Introduction

For many years, simulation has been an essential engineering and design tool that was originally used in two primary sectors: fluid flows and dimensioning of mechanical parts. But to go further in understanding the phenomena and in order to predict the in-use properties of parts, engineers have gradually turned to the simulation of complete manufacturing processes.

We speak of 'Virtual Manufacturing' and there are now many software solutions adapted to each type of shaping processes be they for metals, for plastics or many other materials.

The aim of this article is to present a range of possibilities offered by simulation in the field of rheological study and more particularly in the Injecting and molding of polyurethane foam used in the automotive sector.

2. Rheological simulation

2.1 Application to standard injection processes

The simulation of the plastic injection process makes it possible to virtually visualize the advance of the material front during the filling of the mold. The objective is to detect before production any kind of defect that could alter the properties of the injected parts and to propose solutions to guarantee better quality and greater productivity.

The technique applies just as well for existing designs as for new configurations. In both cases, it is easy to test several operating conditions (thermal regulation of the molds, holding pressure, position of the feed channels, closing force, etc.).

Any defects (incomplete, weld lines, shrinkage, burns, excessive deformation at shrinkage) are identified and the process can be optimized (closing force, cycle time, packing pressure ...).

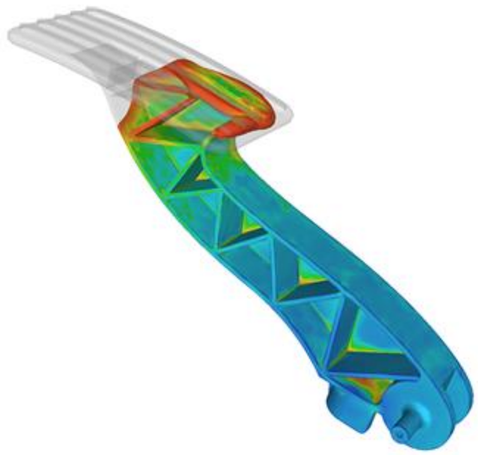

Figure 1: Temperature distribution during injection of a reinforced PA66 pedal

Figure 1 presents a relatively simple application which corresponds to a widespread use in engineering and design offices. Today, software advances make it possible to go even further by addressing more complex problems:

- Optimization of sequencing during a multi-point injection
- Channel balancing for multi-cavity injections
- Control of wall thickness for hollow parts produced by assisted injection (water or gas)

- Distribution of the materials in co-injection to avoid in particular the phenomenon of drilling
- Prediction of fiber distribution and orientation for loaded materials.

This last point is fundamental for technical parts for which in-use properties have to be guaranteed.

2.2 Application to PU foam injection and molding

Production of cellular materials (foamed) is a rapidly growing field today.
Foaming may be physical as in the MuCell® process. The aim is then a weight reduction which can reach a few tens of percent, accompanied by an improvement in dimensional stability.
Foaming can also be chemical. It is produced by the addition of a foaming element to the base polymer. This is particularly the case for the PU foams to which we are interested in this article. This process creates a more aerated cellular material. The structure is obtained by a gas evolution resulting from the exothermic polymerization reaction of an isocyanate combined with a polyol [1].
The PU foams allow the production of semi-finished products (blocks, rods) or directly molded parts to the desired geometry. This is called "in situ" foaming. The automotive sector leverages this process more particularly for interior parts with rigid foams for dashboards (Figure 2) or steering wheels, and flexible foams for seats or certain fittings.

For the simulation software, this process remains relatively complex because several physical phenomena occur at the same time. For example, the simulation must consider the strong coupling between mechanics, thermal and chemical kinetics.

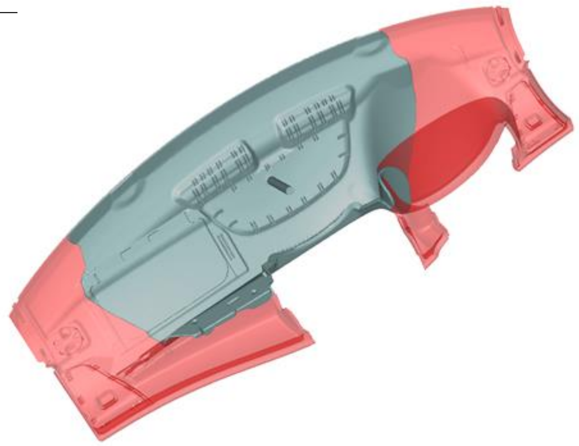

Figure 2: Expansion of PU foam with material front during filling of a dashboard

Thus, the rheological study must take into account the different molding conditions and satisfy very specific requirements among which:

- Manage flexible, semi-rigid and rigid foams through appropriate rheological laws
- Take into account the initial phase of foam deposition followed by the expansion phase
- Evaluate the flow in the cavity by modifying the injection thresholds, balancing and inclination of the mold
- Determine the minimum mass to be injected and the overpacking
- Optimize the number and location of vents to avoid incomplete castings
- Predict final density in both mean value and more locally
- Identify surface defects
- Limiting scraps and final cuts

3. Advanced features

As stated previously, the process remains complex to simulate. For this reason, we will explain in this section the main points that differentiate the REM3D® software and enable it to simulate the injection-expansion process of PU foams with precision.
As often the quality of the result relies on:

- a fine description of the material behavior
- the software capability to take into account the specificities of the process
- The choice of digital techniques adapted to the complexity of the problem.

3.1 A complete rheological model

Like most polymers, the flow of polyurethane foams is governed by the classical Navier-Stokes equations and by the heat equation:

$$\rho\left(\frac{\partial v}{\partial t} + v\nabla v\right) - \nabla\left(2\eta\varepsilon\left(v\right)\right) + \nabla p = f^{v} \qquad [1]$$

$$\frac{d\rho}{dt} + \rho\nabla . v = 0 \qquad [2]$$

$$\frac{d(\rho c\ T)}{dt} = \nabla . k\nabla T + S \qquad [3]$$

With the terms: velocity v, pressure p, density ρ, Dynamic viscosity η, stabilization function f, temperature T, specific heat c_p, thermal conductivity k and a source term S for viscous dissipation and polymerization reaction [2].
The evolution of the gas ratio is calculated according to:

$$\frac{d\phi}{dt} = G(\phi, t, T) - \chi_p f \frac{dp}{dt}(1-\phi) \qquad [4]$$

The generation of gas in the foam causes a density evolution which is taken into account in the Navier-Stokes conservation equation:

$$\nabla . v = -\frac{1}{\rho}\frac{d\rho}{dt} = \chi_p \frac{dP}{dt} - \frac{1}{(1-\phi)G(\phi, t, T)} \qquad [5]$$

3.2 Coupled consideration of injection and expansion

The coupled resolution of the above equations makes it possible to model the process by taking into account the phenomenon of expansion as soon the injection phase started. This is essential since the expansion begins gradually from the foam deposits.

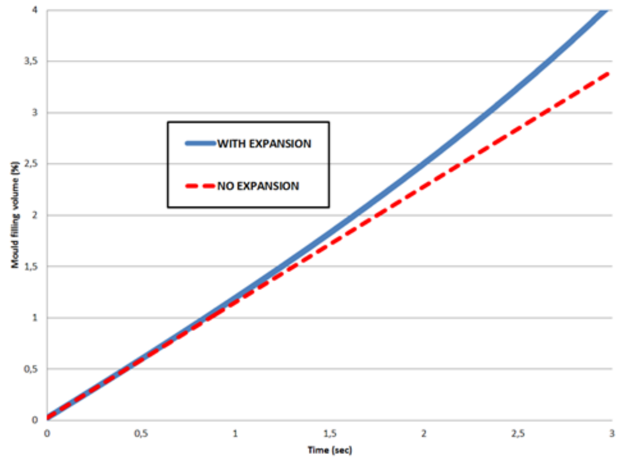

Figure 3: Variation of the filling rate with or without expansion during the injection phase.

Considering the two phases as totally independent can lead to an erroneous estimation of the required mass of foam and overestimated filling times.
FIG. 3 illustrates simulation results with the variation of the filling rate in the mold during the foam injection phase. The lower curve corresponds to the theoretical volume following the imposed constant flow. The upper curve shows the total simulated volume with a marked increase due to the expansion that begins during the injection.

3.3 Specificities of the process

The injection-expansion of PU foam has certain specificities and it is important for the simulation software to appropriately represent them.

<u>The foam deposition phase</u>: it can be carried out with mobile injectors which are robotized or simply manipulated by an operator. The simulation software must be able to reproduce this reality by allowing the definition of a trajectory for one or several injectors. The foam deposition phase is thus clocked in time and space.

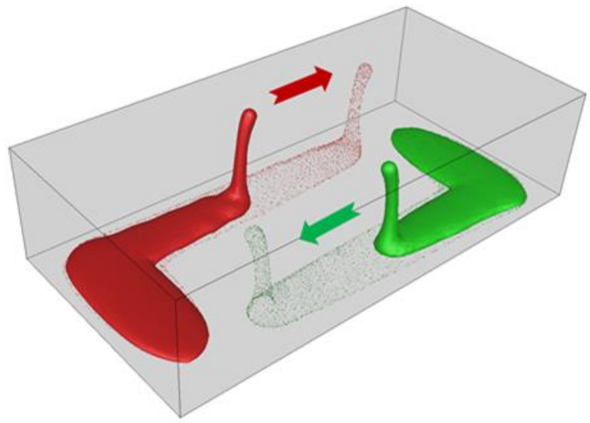

Figure 4: Simulation on 'test' geometry illustrating the deposition of two foams by mobile injectors

<u>Molds with variable tilt:</u> this adjustment option makes it possible to better control the direction of expansion of the foam by favoring an expansion from bottom to top. On production lines for automotive seat parts, this angle of inclination may be, for example, between 30 ° and 45 °. The “aesthetic” faces of the part are traditionally oriented towards the lower part of the mold in order to avoid the risks of surface defects (bubbles, etc.).
In addition, the simulation includes the definition of vents that have a double role: - eliminate defects related to air trapping phenomena and
- allow the evacuation of any surplus material.
The simulation results (see figure 5) show the impact of the angle of inclination on the filling of the mold. Under the combined effect of the expansion reaction and gravity, the foam does not occupy the same parts of the mold

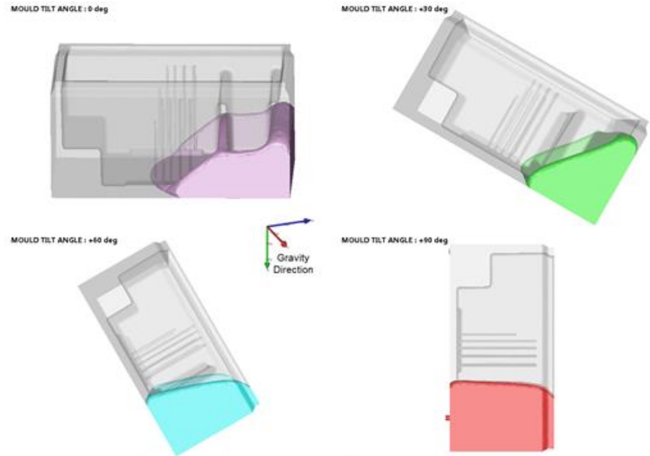

Figure 5: Impact of the angle of inclination of the mold during the expansion phase (30% filling)

It can also be seen from FIG. 6 that the time required to fill a given percentage of the cavity decreases as the angle of inclination increases.

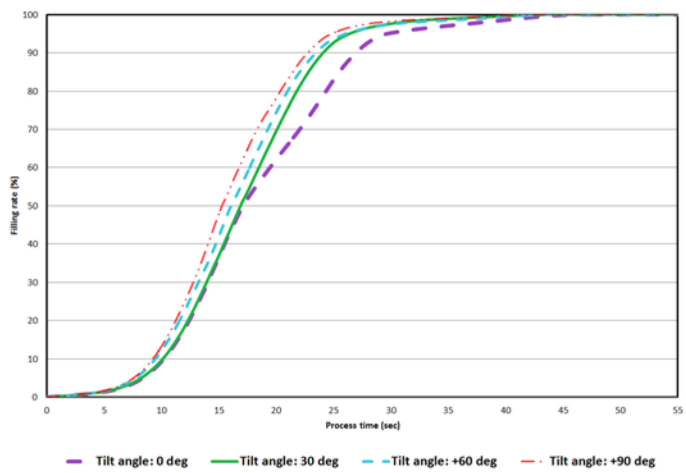

Figure 6: Variation of the filled volume (in%) according to the angle of inclination of the mold (0-30-60-90 deg)

The simulation software allows the designer to virtually test the inclination of the mold to guarantee the filling quality and optimize the cycle times.

3.4 The AAA remeshing technique

In general, the flow is calculated within the cavity using a 3D Eulerian approach. The total volume calculated includes both the volume occupied by the foam and the volume occupied by the ambient air. To distinguish each of these domains, a presence function is computed using a level-set approach [3].
Moreover, the thermal aspects are preponderant in injection and it is absolutely necessary to have both an adapted mesh to accurately define the boundaries of each domain and a fine resolution in all critical zones (material front, mold walls, local gradients). To achieve this, REM3D® has a unique functionality called Automatic, Adaptive and Anisotropic (AAA) remeshing [4].

<u>Automatic remeshing:</u> fully integrated in the calculation and parallelized, it is very effective on multi-core architectures. The remeshing function is first automatic, that is to say it automatically triggers during the calculation according to local variations or for an overall topological improvement.

<u>Self-adaptive and anisotropic remeshing:</u> during Computation, the mesh is densified and optimized locally for evolutions of complex interfaces and to account for the strong couplings between flow - thermal - rheology.

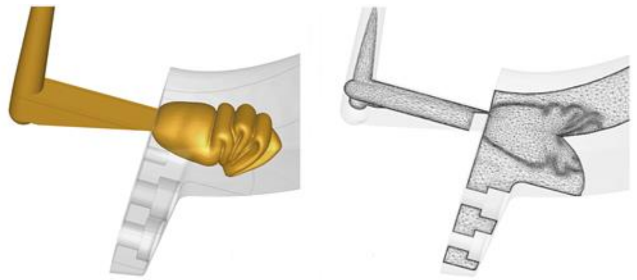

Figure 7: Example of a self-adaptive remeshing in accordance with the evolution of the material front.

FIG. 7 illustrates the high refinement applied to the polymer / air interface. A method with an error estimator makes it possible to optimize the mesh at each time step according to one or more adaptation functions. In this way, a high degree of precision is obtained in the sensitive zones while retaining a limited number of nodes in the finite element model.

Several adaptation functions are thus combined for optimized refinement:
• A characteristic function of the interfaces and the material front
• A characteristic function according to the standard of speed and temperature
• A characteristic function depending on the contact with the walls

4. The advantage of characterizing foams

Whatever the quality of the models implemented, the simulation will provide predictive results provided that it is supplied with appropriate material data. It appears that for PU foams there is very little rheological data available in the literature and the variety of formulations further complicates.
To overcome this challenge, we present here a methodology that combines technical equipment for the measurement of physical parameters and a numerical approach to convert the measured parameters into data that can be used by the REM3D® software.

4.1 The Foamat® characterization system

This equipment illustrated in FIG. 8 makes it possible to carry out characterizations adapted to flexible, semi-rigid or rigid foams. From a formulation sample, the expansion is carried out at controlled volume. The reaction temperature is measured during the expansion via a sensor inserted within the sample itself.
Several physical parameters are thus measured simultaneously:
• The reaction temperature
• The rise height (or expansion speed)
• Pressure

Figure 8: Description of the characterization system (with the authorization of Format_Messtechnick GmbH)

Since the formulations can be quite variable, the major interest lies in the ability to measure the exact formulation used for the real part. This is part of a true quality control approach to better control the simulation within the design chain.

4.2. Use of material data for simulation

The second phase of the methodology consists in using an automatic optimization algorithm coupled with the simulation software. The actual controlled expansion test is simulated under the same conditions. A so-called 'point tracking' feature allows the simulation to record values such as temperature at any point in

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the part. This record is therefore comparable with the curves recorded during the actual test.

The optimization algorithm is based on a minimization principle. The rheological behavior of the material is described by nearly ten parameters. As in an experimental plan, the values of these parameters are automatically tested and a simulation is started for each set of parameters chosen.
Optimization consists in minimizing a cost function which calculates the difference between the actual curves and the curves calculated from the simulation:

- Deviation from the curve for the evolution of the temperature at a reference point
- Curve deviation on the rise height profile.

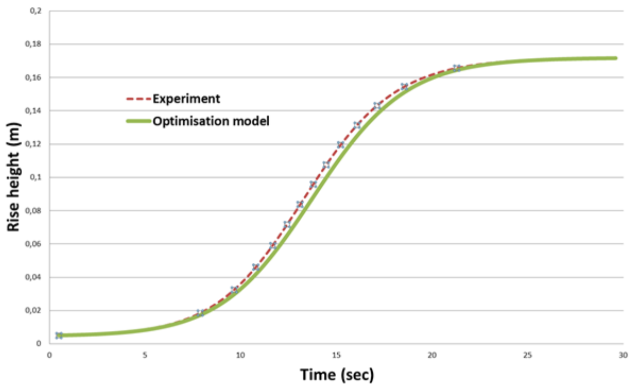

Figure 9: Comparison of climb height profiles (experimental values and values obtained by optimization)

Once the optimization has been completed, the material parameters now identified are integrated into a material file that will be used for simulations related to this precise formulation.

5. Panorama of industrial applications

The simulation for injection-expansion of PU foam concerns a wide range of automotive parts.

5.1 Dashboard

In this example, we present the evolution of the front during filling. The injection is made from a single point centered on the part. The foam deposition phase is relatively large with 1.25 kg of foam deposited during nearly 30% of the filling. The distribution of matter is relatively balanced with nevertheless a predominance of the flow on the left part of the piece.

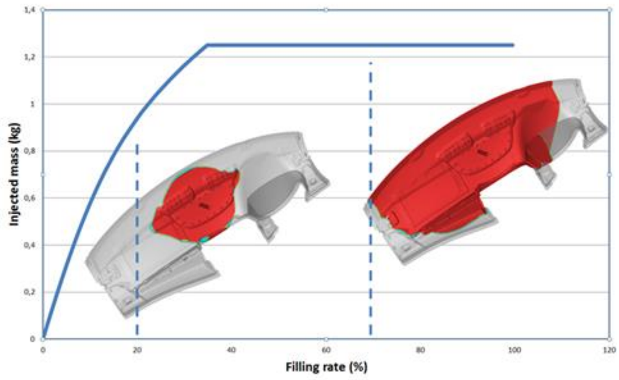

Figure 10: Increase of the material front (20% And 70% filling) with superposition of the Injected mass.

5.2 Indoor Equipment Panel

In this example, the simulation predicted the minimum mass to be injected for a large inner panel measuring more than 2.5m long. The analysis during the filling makes it possible to visualize the competitions of flow and to detect the possible welding lines.

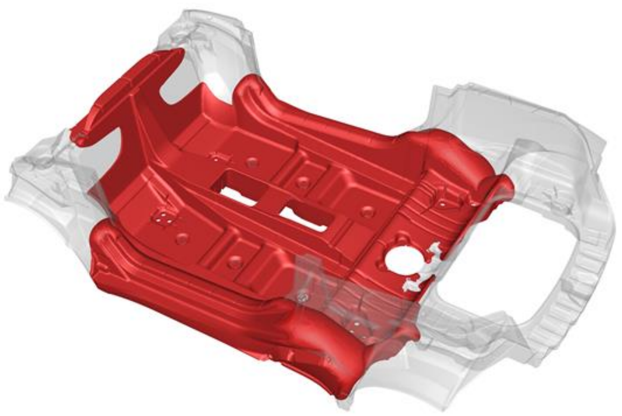

Figure 11: Evolution of the foam front during the expansion phase

For this type of part, the prediction of the final density is very important because it conditions the characteristics of the part. Depending on the mass injected, the simulation makes it possible to quantify the density at any point of the part. Figure 12 illustrates the use of cutting planes to locally measure the final density and to establish longitudinal or transverse profiles.

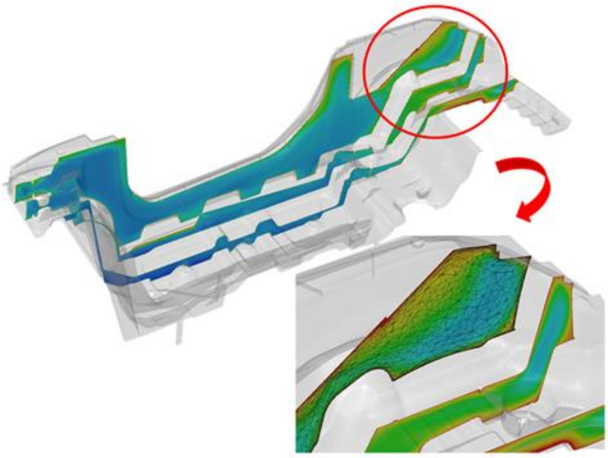

Figure 12: Sections representative of final density of foam (100% filling)

5.3 Vehicle Seat

This example illustrates the foam molding of a vehicle seat using an inclined mold. The term "tilt" is often used to designate this rocker of the mold. The simulation reveals the surface defects observed mainly on the underside of the seat. These defects are linked to insufficient evacuation of the air (trapping phenomenon) or to welding lines. The tests on the position of the vents will correct this type of situation and improve the quality of the finished product.

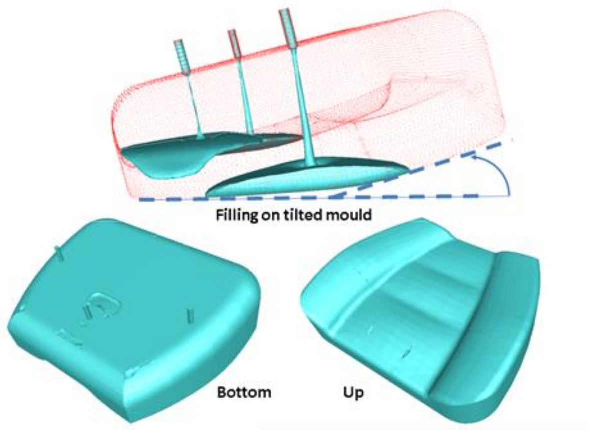

Figure 13: Phase of deposition of foam on inclined mold - Final shape with surface defects on the underside

6. Conclusion

The PU foam injection and molding process is now one of the manufacturing processes used in the automotive sector for which the simulation remains unused or little used. As explained in detail, this process has several specificities and the REM3D® software has a perfectly adapted functional panel that allows rheological studies for truly industrial configurations.
Thus, simulation for foam molding can be perfectly integrated into the design chain and allows an end-to-end optimization:

- injection conditions
- balancing and tilting of the molds
- thermal variations of the mold
- minimum mass to be injected
- reduction of material losses at the vents
- testing of more or less reactive foams
- reduction of cycle times.

In addition, the simulation tool improves the prediction of usage properties by providing a density map at any point in the part to meet the requirements of a specification for expected behavior (sound insulation level or Thermal, or structural requirements).

In the longer term, the goal for injection-expansion of reactive foams simulation will be to increase the predictive quality for increasingly complex geometries. This will require better control of numerical models and related data, as well as functional changes that will allow us to better represent the reality of the process.

7. References

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8.Glossary

PU ou PUR : Polyurethane

AAA : Automatique Adaptative Anisotropic