Determination of Robust Conditions for Injection Moulding of Recycled Polypropylene

A. Cellere[1], G. Lucchetta[2]

[1]*DIMEG – University of Padova - Via Venezia, 1, 35131 Padova, Italy*
URL: www.dimeg.unipd.it *e-mail: Alessandro.cellere@unipd.it*

[2]*DIMEG – University of Padova - Via Venezia, 1, 35131 Padova, Italy*
URL: www.dimeg.unipd.it *e-mail: giovanni.lucchetta@ unipd.it*

ABSTRACT: The aim of the robust design method is to determine the process conditions that minimize the influence of external noise factors, such as varying environmental conditions and material characteristics. In particular, in the injection moulding of recycled polymers, the properties of the raw material are subjected to significant variations due to changes in the mixtures, frequent batches changes and difficulty in controlling the characteristics of incoming materials. In this paper numerical simulations were used to test the influence of the rheological properties of recycled polypropylene blends on the warpage of a plastic component. The planning of the simulations was designed in according to the Mixture Design technique, and the polymer blends were characterized by rotational and capillary rheometers, to get the experimental rheological curve for both low and high shear rates. Experimental results were fitted to the Cross-WLF model, and then implemented into Moldflow Plastics Insight© to predict part warpage. Monte Carlo simulations were used to determine the probability distribution of two responses in terms of part warpage and to determine robust conditions to maintain warpage within designed tolerances.

Key words: Injection Moulding, Monte Carlo simulation, Warpage

1 INTRODUCTION

With the ever increasing price of oil the use of recycled polymers is becoming an economical alternative for the injection moulding of many commodity plastic parts, such as pet and gardening products. However, the properties of the blends of recycled plastics are subjected to significant variations due to changes in the mixtures, frequent batches changes and difficulty in controlling the characteristics of incoming raw materials [1]. These properties can be regarded as probabilistic variables, each one having a mean value and a corresponding standard deviation that can be used in a reliability assessment of the injection moulding process.

The aim of this paper is to evaluate the use of the Monte Carlo simulation technique combined with a special response surface technique called ‘Mixture Design’ to approximate the influence of recycled polymer blends viscosity on the warpage of injection moulded parts.

In the Monte Carlo analysis several experiments were designed considering the distribution of the blend rheology as a probabilistic variable. These experiments are numerical simulations, carried out using the software Moldlflow Plastics Insight®, from which the warpage results then were used to determine the probabilistic response. Several thousand experiments are required for a probabilistic evaluation of the numerical model. Since a single computer simulation of the injection moulding process takes usually several hours to complete, a direct computation of all the experiments was not feasible [2].

Instead, the Response Surface Methodology (RSM) for mixture designs was used to locally approximate warpage results of the simulations. These surfaces can be described by polynomials of any degree but linear or quadratic surfaces are commonly used [3-4]. They were then used in the robust design of the blend composition.

As an example, the proposed method has been applied in this work to describe the influence of the blend composition on the warpage of a 3-component mixture of recycled PP and to determine robust conditions to maintain warpage within designed tolerances.

2 ROBUST DESIGN OF THE INJECTION MOULDING PROCESS

The basic concepts for Monte Carlo analysis and Mixture Design are briefly explained below.

2.1 Monte Carlo analysis

The Monte Carlo method is based on the generation of multiple trials to determine the expected value of a random variable. As used here, Monte Carlo simulation is more specifically used to describe a method for propagating uncertainties in model inputs into uncertainties in model outputs. Monte Carlo simulation relies on the process of explicitly representing uncertainties by specifying inputs as probability distributions.

A Monte Carlo simulation follows five simple steps that can be easily implemented in a spreadsheet for simple models:

1. Define a parametric model $y = f(x_1, x_2, ..., x_q)$.
2. Generate a set of random inputs, $x_{i1}, x_{i2}, ..., x_{iq}$.
3. Evaluate the problem deterministically for each y_i.
4. Repeat steps 2 and 3 for $i = 1$ to n.
5. Analyze the results.

Several thousand simulations are required for a probabilistic evaluation of the numerical model. To keep the number of simulations of the injection moulding process reasonably low response surface models can be used according to the Design of Experiments and Mixture Design methods, respectively to describe the influence of the main process parameters and the blend composition.

2.2 Mixture Design

A mixture experiment is a special type of response surface experiment in which q factors are the components of a mixture and the response is a function of the proportions of each component [5]. For mixture experiments, the sum of the component fractions must be equal to unity and their proportions must be non-negative:

$$\sum_{i=1}^{q} x_i = 1 \quad (1)$$

$$x_i \geq 0 \qquad \text{for i = 1, 2, ..., q} \quad (2)$$

In mixture problems, the purpose of the experimental program is to model the blending surface with some form of mathematical model so that predictions of the response for any mixture of the components can be made empirically. In general, a polynomial model is chosen, which takes a canonical form because of the constraint (1). The most typical models to represent the mean of the response variable (y) as a function of the q factors xi using regression coefficients β_i, β_{ij} and β_{ijk} are the linear (3), the quadratic (4) and the special cubic model (5):

$$y = \sum_{i=1}^{q} \beta_i x_i \quad (3)$$

$$y = \sum_{i=1}^{q} \beta_i x_i + \sum_{i<j}^{q} \beta_{ij} x_i x_j \quad (4)$$

$$y = \sum_{i=1}^{q} \beta_i x_i + \sum_{i<j}^{q} \beta_{ij} x_i x_j + \sum_{i<j<k}^{q} \beta_{ijk} x_i x_j x_k \quad (5)$$

The linear model is used when the effects of the components in the mixture are additive and the response variable can be defined as linear combination of their fractions. The quadratic model considers antagonistic (β_{ij}<0) or synergic (β_{ij}>0) interactions between pairs of components of the mixture, whereas the special cubic is able to consider interactions between three components.

In the present research, a {q,m} simplex lattice design for q components is proposed in order to study the part warpage as a response. In this design the proportions assumed by each component take the m+1 equally spaced values from 0 to 1, where m is the design degree:

$$x_i = 0, \frac{1}{m}, \frac{2}{m}, ..., 1 \qquad \text{for i = 1, 2, ..., q} \quad (6)$$

This is a boundary-point design, i.e. all the design points (treatments) are on the boundaries of the simplex. In the case of three components, the factorial space constituted by all the possible fractions of the components is a triangle whose vertices correspond to pure components, as shown in Figure 1.

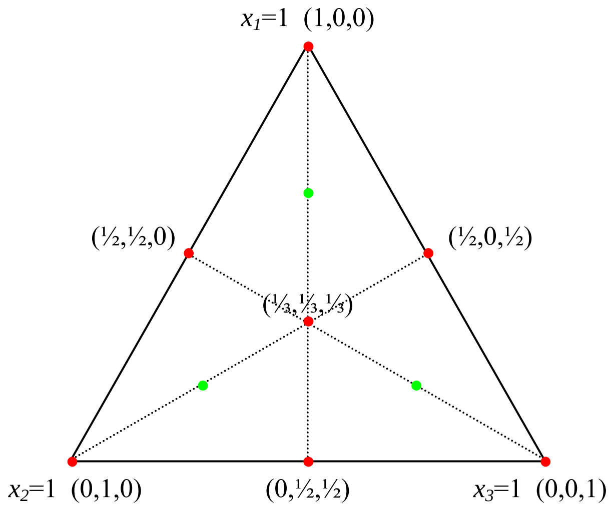

Fig. 1. Configuration of experimental runs for a {3,2} simplex lattice design.

The total number of experiments is calculated as follows:

$$n = \frac{(q+m-1)!}{m!(q-1)!} \quad (7)$$

Since for numerous components and high degree designs the number of runs may become too large, it is proposed to use only second-degree designs augmented with a point at the centre (centroid) of the simplex. This allows the experimenters to employ the quadratic model (4) and, therefore, to take into consideration a possible curvature of the model. Eventually, q experimental runs are proposed to be performed at the axial points in order to test the validity of the model.

3 CASE STUDY

The numerical simulations were conducted on an automotive component, a box for batteries, shown in Figures 2 and 3. This part is normally produced on a 8200 kN injection moulding machine, using different blends of polypropylene. The mould cavity is fed by a hot runner injection system, with six gates. Quality requirements are imposed on the part dimensions, especially on the flatness of the top rim and the linearity of the longer sides. These dimensional tolerances are necessary in order to allow the welding of the lid. The aim of this case study is to determine robust process conditions to minimize the deformations in these two directions, improving the quality of the moulded component.

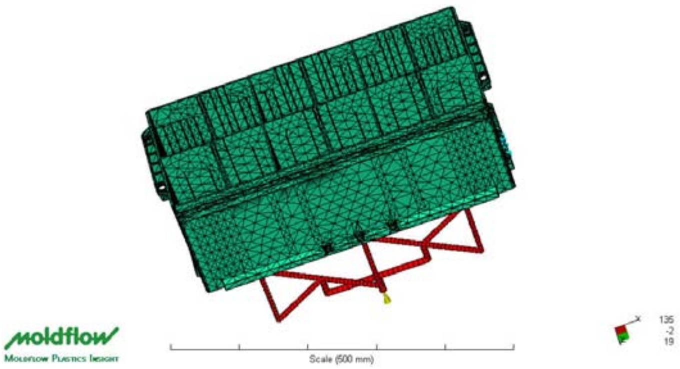

Fig. 2 Fusion mesh of the box modelled with Moldflow Plastics Insight®

3.1 Numerical model

The injection moulding process was analyzed by means of Moldflow Plastics Insight®. Both the part and the feeding and cooling systems of the mould were modelled with the 36751 element fusion mesh shown in Figure 2. The main process parameters were set-up considering the real production values and are reported in Table 1. These process parameters were considered as control variables while the blend composition was chosen as the noise variable.

Table 1. Main process parameters

Parameter	Value
Melt temperature [°C]	250
Mould temperature [°C]	50
Packing pressure [MPa]	45
% vol. filled at switch-over	98
Cooling time [s]	20

The control of the velocity/pressure switch-over was set as a percentage of volume filled, and the cooling time was set to 20 seconds.

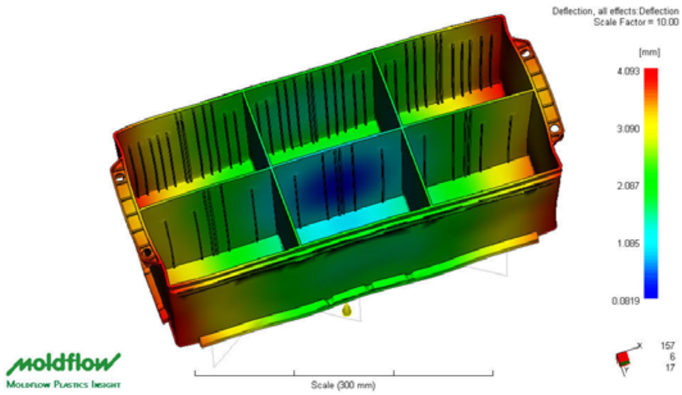

Fig. 3 Example of warpage analysis, with 10X scale factor.

3.2 Mixture design of the numerical simulations

Three different polypropylene components were blended in a molten state by means of a screw extruder and according to the designed mixtures shown in Figure 1. The extrudates were then pelletized and loaded into the reservoir of a constant-rate capillary rheometer, CEAST Rheologic 2500.

A rheological test was then carried out for each run of the experimental plan, according to the ISO 11443 standard. The actual run order was randomized to counteract any time-related effects, such as the degradation of material. Each treatment was replicated at least twice to get a measure of the experimental error. Rheological tests were also conducted on a rotational rheometers, TA Instruments ARES, at three different temperatures to measure the viscosity at low shear rates and estimate its temperature dependence.

Experimental results were fitted to the Cross-WLF model, and then implemented into Moldflow Plastics Insight© to predict part warpage. Linear and quadratic mixture models were then fitted to the experimental data by least squares regression. The adjusted R^2 and the p-values for the F-test and the lack-of-fit test were calculated. According to these figures, the linear model was chosen since it had the largest value of the adjusted R^2.

Eventually, three experimental runs were performed at the axial points in order to test the validity of the model. The experimental measures were in good agreement with the relevant predicted values.

3.3 *Monte Carlo simulations*

The resulting normal distributions for the two responses are given in Figure 4 and 5. Based on these results it is possible to determine the probability for the response have a value between two bounds. This allow us to determine, for example, the percentage of production scrap. Design specifications impose a maximum flatness of 3.5 mm and a maximum warpage of 4 mm. With the nominal process parameters flatness results are completely out of range while only a small percentage of parts present an unacceptable warpage.

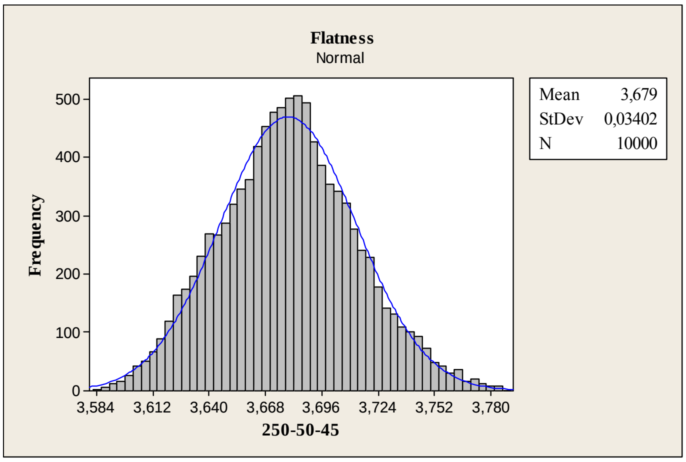

Fig. 4 Probability density functions of the top lid flatness at nominal process conditions

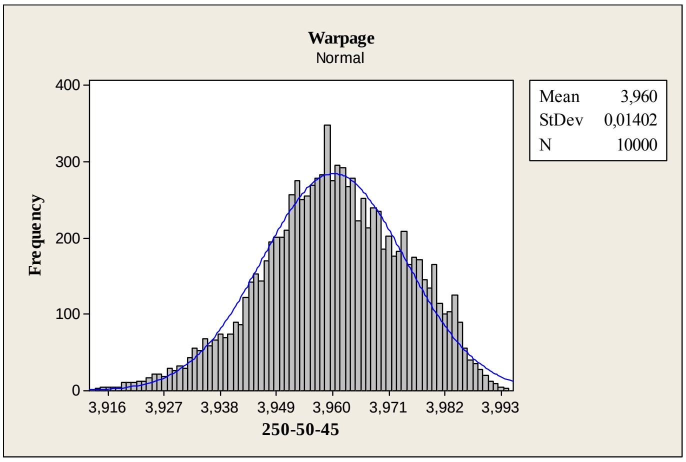

Fig. 5 Probability density functions of the longer sides warpage at nominal process conditions

By changing the values of the control variables (T_{mold}=30°C, P_{pack}=45 MPa), it is possible to shift towards lower and acceptable values both the response probability density functions and to improve part dimensional consistency by decreasing their standard deviations.

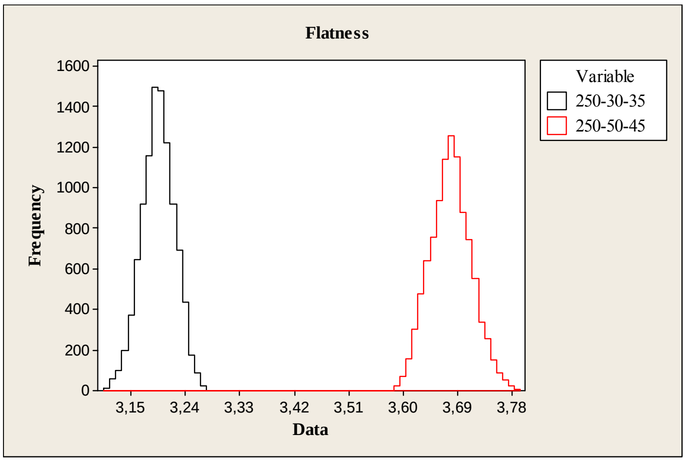

Fig. 6. Probability density functions of the top lid flatness at different process conditions

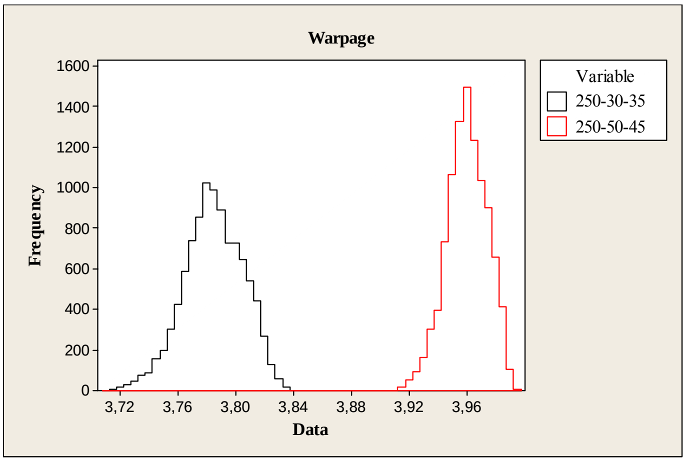

Fig. 7 Probability density functions of the longer sides warpage at different process conditions

4 CONCLUSIONS

Monte Carlo simulations were used to determine the probability distribution of two responses in the numerical simulation of an injection moulding process. The result from the Monte Carlo simulations can be used to determine robust conditions to maintain warpage within designed tolerances..

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