Advancements in Warpage Control in Injection Molding and Mathematical Modelling with Python

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Abstract: Popular plastics today are applied in different industries because of their flexibility, low density, and ease in the production procedure. Plastic injection molding is a good technique used in molding food products because it enables the production of high quality and intricately designed plastic parts which are further produced in large quantities. However, when cooling shrinkage and warpage occur the dimension of the molded parts is usually compromised hence reducing performance. While warpage is the distortion of the part that happens due to the formation of internal stresses, shrinkage refers to the dimensional variation as the material cools down. These defects are due to properties of the material, the mold design as well as the process parameters in operation. Several measures and strategies including the optimization of the molding conditions, in-mold decoration, microcellular injection molding and many others have been employed to reduce these effects. This paper focuses on the recent innovations regarding warpage control to establish the effect on the quality of the final product and production effectiveness. This paper exhibits how warpage defect can be described using nonlinear regression analysis that was derived using full factorial design (FFD).

Keywords: - Plastic Injection molding, warpage, FFD, optimisation, nonlinear Regression mathematical modelling,

1. INTRODUCTION

Plastics are therefore flexible light weight and cheap materials which can be used in number of applications. Metal gears are also advantageous because they have extensive use, versatility, and manufacturability for use in vast production. Shrinkage happens when the coin cools unevenly and therefore it causes the part to develop the wrong shape of required dimension. An instance is shrinkage that is experienced with plastics whereby the product shrinks in size and causes deformation when cool. These defects have been found to have attributes to do with material properties, mold design and characteristics of the process being used. Mishra et al have also noted that inadequate control of cooling, pressure and mold temperature can lead to the above problems in the research work done by them [1].

S.yu et al. made findings that warpage control in injection molding is very important in order to control dimensional stability and quality of parts in the manufacturing of product especially for highly complex processes such as IMD and MIM [2]. New Technologies like double side embedded molded interconnect device MIM and so on revive temperature fields and optimise both the cellular and fibre distribution so as to minimize warpage.

In the paper of S. yu et al., the authors introduce the D-IMD/MIM process and apply double sided decorative films in microcellular IM in order to minimize the warpage deformation. There is also low tendency of thermal stresses due to balanced temperature and equal distribution of cells. Computer aided simulations and experiments on the developed spline sample revealed that warpage was reduced to 71.68% the value of S-IMD/MIM. One of the core-formed cells are fairly concentrated and there is only small distortion in cross sections. Warpage is also restricted in D-IMD/MIM process making the quality of the produced products better.

There are reports regarding things like the kind of material, the process of preparation, and addition of nucleating agents so as to increase crystallinity and mechanical properties. These approaches include predictive modeling and methods with FMEA and Bayesian networks that help in the identification of root risks about warpage. These fall in line with sustainable polymer engineering by solving problems regarding recycled polymers and lightweight products fabrication[3].

Hopmann et al. deals with practice behaviour of the specific volume for polymers that are critical to avoid shrinkage and warpage using the injection moulding method. It emerges from this research that it is possible to use a model predictive control for the dynamic segment mould temp. And enhanced pressure volume & temp model. From the theoretical analysis outlined above, it can be inferred that the cooling rate works with the model and is further checked with experimental results of measured values using figure 2 below. Concerning the impact of the parameters, results focus on the definite influence of the cooling rate on final specific volume predictions. As a result, it was seen that FDM simulation is very much effective in judging post ejection cooling and takes 60 minutes to come to an ambient temperature of 23°C.

As pointed out by T. Lang et al., the risk in the plastic R & D laboratories happens through the material influence of production parameters. In his research, the FMEA, fuzzy BWM, and rule-based Bayesian networks approach were adopted to give an integrated approach in identifying 15 failure modes. For the root risks, the highest risk is non-homogeneous mixtures with extrusion failures being the biggest risk category (CRV: 0.564059). Because it assesses risk in terms of severity, occurrence, and detection it provides a clearer picture of the risks as graded by the different risk assessment models. This work underlines a high level of variability for the extrusion as well as the injection process and shredding as highlighted in the results section.[5]

Tabi et al. is more concerned with enhancing the crystallinity of PLA and its mechanical properties in injection molding application. Increase HDT, flexural and tensile strength and Young's modulus of low D-lactide PLA were carried out by addition of nucleating agents (PPZn, Ecopromote, Ecopromote HD) and plasticizers (OLA, DOA). The crystallinity of the materials was east strongly by the "cold mold 'temperature range of 25-50" during the cooling stage to make the material stiffer and the "heated mold temperature of 85-135" that enables in mold crystallization. The improvement in the tensile properties achieved in the current work was also accompanied by the unfavourable characteristic of brittleness in which elongation at break difficulty stayed in the range of 1.7 to 2.5%. Thus, even with these improvements, it was impossible to achieve the maximum crystallinity of PLA during molding.

In an article by J. Gim et al., the author discusses the methods of injection molding for obtaining excellent surface quality and such aspects as dimensions, influential factors, prediction, and control of surface defects. It brings out the increasing concern on surface quality issues of the applied recycled polymer materials due to attributes such as homogeneity, thermo degradation, and addition. In this paper specific focus is made on carrying out the research concerning the improvement of the surface quality for the polymer engineering for sustainability.

In particular, S. Yu et al. describes the specific process of applying ID as double-sided IMD and FRP-IM to obtain lightweight and high-quality products. Microcellular structures are developed with the help of Supercritical fluids while the use of glass fibers contributes towards the improvement of mechanical properties. This process makes the surface luminous, it also hides defects, facilitates the control of fiber and cellular distribution and increases gloss.

Compared and contrasted to other works, DS-IMD/FR-MIM demonstrates 10.2% reduction in the weight, 24.3% increase in elongation at break, 170% increase in tensile strength and 80.2% in the flexural strength. A tentative process allows manufacturing lightweight but strong and aesthetically pleasing molded parts according to the author.

Kumar et al. aspires to enhance the IS of spherical polypropylene parts in the process of plastic injection molding while decreasing the extent of thermal shrinkage as well as warpage of the tiny balls. By employing the Taguchi method, ideal conditions for the process parameters were established, and therefore minimum shrinkage (4.67%) and warpage (2.2mm) as well as maximum (63C) was recorded. Impact strength (64.5 J/m). Temperature of the melt media, the temperature of the mold and the injection pressure was established to be the most effective parameters.

The researching mathematical models for Impact strength, shrinkage, and warpage and these models were optimized using Multi-objective Genetic Algorithm. The forecasting errors with regard to shrinkage, warpage, and is where small, making the process readily applicable in the industrial setting.[9]

2. CASE STUDY ON WARPAGE WITH FULL FACTORIAL DESIGN (FFD) IN THE PYTHON-SPYDER CODING

The current research applied Spyder coding for the Full Factorial Design (FFD), which is used to determine how two important process parameters specifically mold temperature and melt temperature will affect the warpage of injection-moulded parts. This statistical technique is used commonly to study the relationship between several input variables and an output variable warpage in the present study [10].

2.1 Design Structure and Parameters

The variable of the FFD is derived from two essential characteristics of an injection molding process, namely

- Mold Temperature (MT): This factor is adjusted at 40, 50 and 60 degrees Celsius.
- Melt Temperature (Melt T): The levels of Melt Temperature are set as 200, 240 and 280.

In the code, both these parameters are taken at 3 levels for both of them and create an experimental matrix of 3 x 3 with 9 experimental runs as depicted in the table 1.

2.2 Replicates

In order to achieve a higher accuracy of the results and to minimize fluctuations in the results, replicates are incorporated in the design. In this case, each combination of mold and melt temperature is done three times in order to avoid random errors or any other error that might be present in the whole experiment. This results in a total of 27 experimental runs (9 combinations of the factors × 3 replications = 27).

Adding replicates increases the accuracy of the coefficients or parameters of the mathematical model and is associated with a higher R-squared coefficient or coefficient of determination, which predicts the proportion of the variance for the mathematical model and is indicative of the error of the predictions or the Mean Squared Error (MSE).

Table 1: FFD Design

Run	Mold Temperature (^{O}C)	Melt Temperature (^{O}C)	Warpage (mm)
1	40	200	3.9
2	40	240	4.3
3	40	280	4.7
4	50	200	4.2
5	50	240	4.6
6	50	280	5
7	60	200	4.5
8	60	240	4.9
9	60	280	5.3

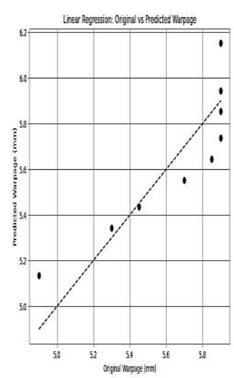

Figure 1: Warpage prediction with linear Regression

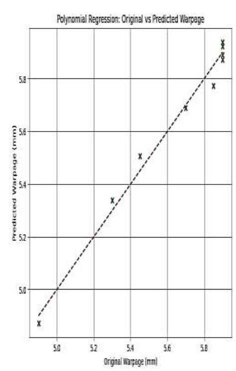

Figure 2: Warpage prediction with Non - linear Regression

Above figures 1 and 2 shows the warpage perdition with LR and NLR .

2.3 Linear Regression (LR) behavioural prediction of warpage

1. Linear Regression supposes a linear dependence of warpage on input parameters – mold and melt temperature.
2. This makes it rather primitive when non- linear effects are at play, which gives wrong estimations in the behaviour of warpage.
3. This leads to smaller R-squared, values and large residual errors, which evidences that LR curve is not capable of modelling the actual measure of warpage.

2.4 Non-Linear Regression (NLR) behavioural prediction of warpage

1. Non-Linear Regression (e.g., Polynomial Regression) provides a good model for capturing the residuals of warpage in relation to input factors as depicted in fig 2.
2. When higher-order terms are included, NLR can account for dependence of parameters on each other much better and as the result, the residual error is quite low.

The enhanced level of-model fitness that is represented by the increased value of R-squared suggests that MHR is significantly more efficient than LR in the process of warpage prediction in injection moulding.

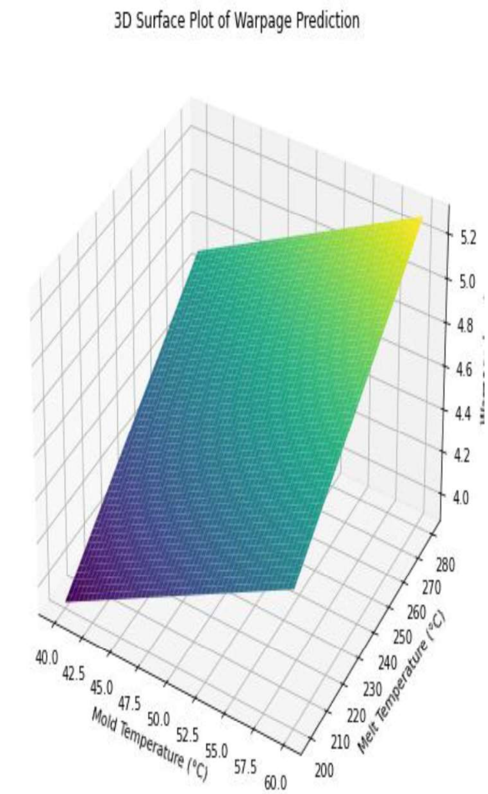

Figure.3: The 3-D Surface plot of Warpage Prediction

2.4 Conducting the Experimental Data on Injecting molding machine

The experimental runs are executed by using the identified experimental values of mold and melt temperature; the warpage values are measured accordingly. In each run, the corresponding warpage 'y' was recorded. The corresponding warpage is then measured for each set of mold temperature and melt temperature as outlined in the factorial design. These data are then compiled and stored in a form of a tabular form known as a Dataframe using the programming language called Python, with a package known as pandas.

2.5 Analysis and Model Building

After the experimental data is obtained, it is employed to create both linear regression and non-linear regression equations. In code eight, the FFD is used to establish the design matrix to generate models for estimating the warpage in functions of the mould and melt temperatures. This is achieved by:

- Focus group business goals: The focus of the linear model is to establish the nature of the association between the input parameters and warpage.
- Non-Linear Regression Model: Since there can be a curvilinear relationship between the factors and warpage, another model is created to capture such trends.

2.6 Model Validation and Performance Evaluation

Performance statistics of the proposed models are measured by two evaluation criteria:

R^2 (Coefficient of Determination): Measures the goodness of fit of the model. Thus, the model explains the variability of warpage better, and a higher R^2 implies better usefulness of the model. MSE (Mean Squared Error): This means the average of the squares of the differences between the predict and real values to the warpage. While evaluating such model, it is desirable that vale of MSE is at its lowest.

X Y-coordinates and the melt temperature for surface graph showing the mold temperature and the effect of the mel, as presented in the fig 3. The 3D surface plot below shows the interface between the mold temperature and the melt, as well as the warpage. The plots highlight the impact of the two vectors of input parameters on the warpage prediction and due to the smoothness of the curves it can be deduced that both input parameters exert a similar influence on warpage. Warpage has been found to increase with increase in mold and melt temperatures and this has been depicted in the figure in the form of a non-linear relationship. This kind of application is useful in determining areas that have little or no warpage and allows one to understand how to tweak parameters to gain better control.

3. OPTIMIZATION AND RESULTS

The analysis of the results shown in Table 4 are arrived from FFD that helps in selecting the best parameters for reducing the warpage, for the injection molding process. This can be particularly useful if the industry concerned requires high quality parts with few imperfections. Thus, by controlling the mold and melt temperatures using the developed regression models, it is possible to minimize the warpage to an acceptable level.

Warpage = 0.03 * mold_temp + 0.01 * melt_temp + 0.7

The non liner regression model (NLR) will provide a more complex but likely more accurate fit with higher R^2 and lower MSE as shown below in Table 2.

Table 2: Comparison LR and NLR

Features	LR	NLR
R^2	0.786	0.985
MSE	0.024	0.0016

4. CONCLUSION

CCD analysis is used in the present work because full factorial design (FFD) in the Python Spyder code incorporates various combinations of mold temperature and melt temperature which influence the resultant warpage as all factors are analysed at once. The convergence of FFD with replicates ensure credibility of the data obtained and the following regressed models give insights to the molding process. This shows that the aspect of warpage in the plastic part is a nonlinear one, which cannot be explained well by the linear regression test. As linear and nonlinear models are used in the study, it clearly shows that the use of linear models is not effective for accurate depiction of the relationship especially when the relationship is nonlinear as the nonlinear gives superior results.

The generated scatter plots also support and explain the efficiency of the predictive results, and the residual part shows how far the results are from the truth. Concerning the graphical representation of the interaction, the 3D surface plot is good enough as it provides an enhanced way of visualizing the trends. This systematic approach can be best thought of as a perfect foundation for selecting the best parameters for reducing warpage. In this light, the following are the degrees of relationship that exists between some of these variables: By realizing such relationships, manufactures can effectively manage the molding process, minimize on the defects and ultimately improve on the quality of the final product. In essence, this methodology is useful in driving process improvement, reduction in cost, and enhancement of efficiency in injection molding.

4. REFERENCES

[1] Mishra, T., Mandal, P., Rout, A. K., & Sahoo, D., A state-of-the-art review on potential applications of natural fiber-reinforced polymer composite filled with inorganic nanoparticle, Composites Part C: Open Access, 2022, 9(May), p. 100298.

[2] Yu, S., et al., Cellular distribution and warpage deformation in double-sided in-mold decoration combined with microcellular injection molding process, Journal of Materials Processing Technology, 2023, 317(March), p. 117982.

[3] Awad, A. H., El-Gamasy, R., Abd El-Wahab, A. A., & Abdellatif, M. H., Assessment of mechanical properties of HDPE composite with addition of marble and granite dust, Ain Shams Engineering Journal, 2020, 11(4), pp. 1211–1217.

[4] Hopmann, C., Xiao, C., Kahve, C. E., & Fellerhoff, J., Prediction and validation of the specific volume for inline warpage control in injection molding, Polymer Testing, 2021, 104(June), p. 107393.

[5] Lang, T., Zhang, J., Qiu, Y., Hong, Z., & Liu, J., A holistic failure modes and effects analysis for university plastic injection laboratory under Bayesian Network, Optik - International Journal for Light and Electron Optics, 2023, p. 129430.

[6] Tábi, T., Ageyeva, T., & Kovács, J. G., The influence of nucleating agents, plasticizers, and molding conditions on the properties of injection molded PLA products, Materials Today Communications, 2022, 32(June), pp. 4–11.

[7] Gim, J., & Turng, L. S., A review of current advancements in high surface quality injection molding: Measurement, influencing factors, prediction, and control, Polymer Testing, 2022, 115(June), p. 107718.

[8] Yu, S., et al., Fabrication of lightweight polymer products with excellent mechanical properties using a novel double-sided in-mold decoration combined with fiber-reinforced microcellular injection molding process, Journal of Materials Research and Technology, 2023, 28(November), pp. 4289–4298.

[9] Kumar, D., Dangayach, G. S., & Rao, P. N., Enhancement of quality of polypropylene by optimisation of injection moulding parameters with genetic algorithm, International Journal of Environmental Sustainability and Development, 2022, 21(1–2), pp. 206–217.

[10] Narukulla, S., Bogadi, S., Tallapaneni, V., Sanapalli, B. K. R., Sanju, S., Khan, A. A., Malik, A., et al., Comparative study between the Full Factorial, Box–Behnken, and Central Composite Designs in the optimization of metronidazole immediate release tablet, Microchemical Journal, 2024, 207(11187), p. 5.