Review of Optimization Aspects for Plastic Injection Molding Process

Mr. Aditya M. Darekar
Research Student
Fr. Conceicao Rodrigues College of Engineering,
Fr. Agnel Ashram,
Bandra (W)

Prof. T. S. Venkatesh
Associate Professor
Fr. Conceicao Rodrigues College of Engineering,
Fr. Agnel Ashram,
Bandra (W)

Dr. Bhushan T. Patil
Associate Professor
Fr. Conceicao Rodrigues College of Engineering,
Fr. Agnel Ashram,
Bandra (W)

Mr Yazad N. Doctor
Research Student
Fr. Conceicao Rodrigues College of Engineering,
Fr. Agnel Ashram,
Bandra (W)

***Abstract*—Plastic molding processes are used to produce plastic parts and components, which finds applications in many industrial as well as household consumer products. Plastic injection molding is really a challenging process for designers, researchers and manufacturers to produce the components or products at low cost, meeting all the necessary requirements from the customers.In today's plastic age, injection molding industry is facing a huge competition. Using a conventional trial-and-error approach for finding out the desired processing conditions for molding is not good enough to sustain in the global market. Many product designing, mold designing aspects as well as large number of process parameters need to be optimized in order to meet customer requirements and expectations regarding quantity, quality and performance of the product at a competitive price. This paper aims to provide an insight of literatures about recent research in optimization aspects for determining optimum process parameters of plastic injection molding.**

Keywords-Plastic Injection Molding; Optimization; Design of Experiments; Simulation; Moldflow Analysis

I. Introduction

Plastic Injection Molding process has been a very challenging process for many manufacturers and researchers to make a component meeting all the expectations of the customer at low cost and in minimum time. In today's rapidly rising market demand, injection molding holds the responsibility of a mass production of the plastic components. Hence every manufacturer has to take care that the cycle time of the molding process is optimized properly to meet the market demand.

But along with reducing the cycle time and lowering the production cost, one of the main goal in injection molding is the improvement of quality of molded parts and maintaining the same throughout all the batches. The complexity involved in the process and the number of process parameters manipulation during real time production creates lot of effort to maintain the process under control. Solving the problems related to the quality of the molding has a direct effect on the expected profit for injection molding industries. [1]

In injection molding, quality characteristics are classified as mechanical properties, dimensional or measurable properties and attributes. In general, some of the main causes of quality related problems are categorized as follows.

- Material related defects such as black specks and splays.
- Filling related problems such as short fills, flash.
- Packing and cooling related defects such as sink marks, voids.
- Post mold related defects such as warpage, dimensional changes and weight change.

Defect mentioned above except material related defects are mainly caused due to improper selection of the processing conditions during production. Traditionally analytical and then experimental trial-and-error approach were used to regulate the molding process for getting good quality and finish on molded product.This trial-and-error process completely depends on the engineers' or manufacturers' knowledge, experience and intuitions to determine initial process parameter settings. Such trial-and-error process is costly and time consuming, thus it is not suitable for complex manufacturing processes like Plastic Injection Molding.

However, Finite Element Analysis (FEA) Simulation using computer software packages has become popular and nowadays preferred in industry because it is cost effective, less time consuming and equally effective in predicting the desired process conditions as well as the defects estimation in product. Simulation technology combined with the optimization techniques have been used for improving design quality and shorten the design cycle.

II. LITERATURE REVIEW

A. Review of Design Considerations and Process Parameters Investigated

P.K. Bharti and M.I. Khan (2010) [1] have classified the factors that affect the quality of a molded part into four categories: part design, mold design, machine performance and processing conditions. They have mentioned that the part design and mold design are assumed as established and fixed keeping all the aspects of injection molding. During production, quality characteristics may deviate due to drifting or shifting of processing conditions caused by machine wear, environmental change or operator fatigue. They have mentioned the main causes of defects in injection molding are mold design, machine performance, operator, type of material and working process parameters.

Ming-ChihHuang and Ching-Chih Tai (2001) [2] carried a simulation analysis on a thin shell plastic mold component using commercial software C-MOLD^{TM}. They have applied Taguchi's experimental method to analyze variation in warpage. They have varied five process parameters viz. melt temperature, mold temperature, filling time, packing time and packing pressure. Along with five process setting they have also included one design parameter that is gate dimension as sixth variable. They found that gate dimension does not have any effect on warpage but both mold temperature and melt temperature are significant factors on variation in warpage. Packing pressure and packing time are also having moderate contribution on warpage variation.

S.H. Tang et al. (2006) [3] have analyzed a thin plate of 120x50x1mm for warpage, they have done ANOVA using Taguchi's L9 orthogonal array. They have got results similar to the findings of Ming-ChihHuang and Ching-Chih Tai. In their conclusion, melt temperature, packing time and packing pressure are significant factors while filling time is not much affecting the warpage defect.

TuncayErzurumlu and Babur Ozcelik (2006) [4] conducted an investigation on injection molded thin rib construction of 300mm x 60mm x 2mm with three different cross-section of triangular, trapezoidal and rectangular shape using simulation and Taguchi method. They have used polycarbonate-Acrylonitrile Butadiene Styrene (PC/ABS), Polyoxymethylene (POM) and Polyamide (PA66) as three different materials for part along with three levels of mold temperature, melt temperature and packing pressure.

HasanOktem, TuncayErzurumluand Ibrahim Uzman (2007) [5] extended their research by conducting simulation analysis on injection molded part using moldflow plastic insight. Their aim was to find the influence of process parameters on shrinkage and warpage and to find the correlation between parameters on both shrinkage and warpage. In their findings, packing pressure and packing time both are significant parameters for shrinkage and warpage.

ZhaoLongzhi, Chen Binghui, Li Jianyun and Zhang Shangbing (2010) [6] conducted a parametric study of melt temperature, mold temperature, injection time, holding pressure and cooling time to find their effect on sink mark index in plastic injection molded component using moldflow software. With the help of parametric study they have optimized the processing conditions for minimum sink marks in automobile dashboard cover.

A. H. Ahmad et al. (2009) [7] also used DOE to study the effect of processing parameters such as packing pressure, packing time, mold temperature and melt temperature on the deflection in the plastic mold part due to warpage.

M. Stanek, D. Manas, M. Manas, and O. Suba (2011) [8] have used Design of Experiments to optimize injection cycle. For gathering the process related data they have used a software and hardware solution called as Moldflow Plastic Xpert (MPX) that interfaces directly with injection molding machine controllers on the shop floor. MPX also has advanced simulation capabilities of simulation package Autodesk Moldflow Insight (AMI) to provide an initial process configuration. Short fills, flashes, sink marks, hesitation marks, color streak marks are defects they have observed on square piece molding during optimization. During optimization, process parameters they have varied includes injection pressure, fill time, packing pressure and cooling time.

Babur Ozcelik (2011) [9] investigated influence of the injection parameters and weld line on the mechanical properties of Polypropylene (PP) during plastic injection molding by using Taguchi experimental method. He determined the optimum injection pressure, packing pressure and melt temperature to get the maximum mechanical strength in injection molding of polypropylene (Dow 765-15NA) material. He have used Taguchi L9 orthogonal array to plot treatment conditions and tested the moldings accordingly for maximum tensile strength, impact strength and extension at break using UTM. He also tested the part on weld line to find strength at weaker section. As per his findings, the most significant parameter affecting the maximum tensile load and the extension at break (both with weld line and without weld line) was injection pressure and melt temperature respectively.

RadhwanHussin et al. (2012) [10] observed warpage defect on plastic shin guard of material PC/ABS using moldflow plastic insight. In addition to other researcher's work they have selected ambient temperature and runner size along with other six process parameters mentioned by Ming-Chih Huang. They found melt temperature to be the most contributing factor with 54.22% followed by runner size with 14.62% and ambient temperature with 11.17%.

M. Kemal Karasu et al. (2014) [11] implemented single minute exchange of dies (SMED) for injection molding. They have also analyzed the progress in change over time without SMED, with SMED and Taguchi's optimization technique empowered SMED. They have found change over time for mold is 90 minutes without SMED and 60 minutes using SMED. After implementing Taguchi method,change over time with SMEDdropped to around 40 minutes. So Taguchi empowered die exchange is less time consuming and more economic.

B. Sha, S. Dimov, C. Griffiths, M. Packianather (2007) [12] conducted design of experiments and data analysis in Micro Injection Molding (MIM). They focused on the analysis with three factors barrel temperature, mold temperature and injection velocity to find their effects on achievable aspect ratios in three different plastics viz. Polypropylene (PP), Polyoxymethylene (POM) and Acrylonitrile Butadiene Styrene (ABS).

Extending B. Sha and others' research, M.Packianather, F. Chan, C. Griffiths, S. Dimov and D. T. Pham (2013) [13] conducted similar experiments in micro injection molded component. Along with previous three factors they have added three more factors that are holding pressure, the existence of air evacuation and width of micro legs. They have conducted 2 level 6 factors fractional factorial design (FFD) with L16 array. Using statistical software Minitab they have plotted Pareto chart of the effects to compare the relative magnitude and statistical significance of main and interaction effects.

C.A. Griffiths, S.S. Dimov, E.B. Brousseau and R.T. Hoyle (2007) [14] studied the effect of tool surface finish on quality of micro injection molding. Along with barrel temperature, mold temperature and injection velocity they added three different surface roughness, Ra values (0.07 µm, 0.8 µm, 1.5 µm) of different mold cavities of same component.

Z. Shayfull et al. (2011) [15] and S.M Nasir et al. (2011) [16] adopted Taguchi method to establish the optimum parameters of injection molding process. They have simulated experiments using Autodesk Moldflow Insight and warpage of ultra-thin shell part was evaluated.

As per above literature and findings of researchers, it is clear that lot of research has been carried out in the field of optimization procedures and technique for injection molding process. Researchers have mainly worked on the quality improvement and elimination or reduction of the defects such as warpage, shrinkage and sink marks by proper selection and optimization of different process related and design related factors such as melt temperature, mold temperature, injection time, packing time, packing pressure, gate dimensions, runner size etc.

B. Review of Optimization Techniques used

As discussed earlier, Plastic Injection Molding is a complex process involving many parameters related to processing, designing, tooling which affects the quality of molding. It is very important to find the correct value for each parameter for getting good quality. Therefore optimization is must for every batch of molding. Right from the birth of plastic molding, optimization techniques are getting improved over the period of time. Previously optimization used to be experimental, but such trial and error experiments were very extensive and time consuming. Then with the advent of new engineering knowledge and research work, analytical approach of optimization started to take shape. But due to the complexity of the equations and calculations, it was difficult to deal with it using standard mathematical techniques and for a person on a shop floor it was not easily possible. In today's computer aided engineering world, it is easy to optimize the molding process with the help of computer intelligence and virtual Finite Element Simulations.

P.K. Bharti and M.I. Khan (2010) [1] also studied various optimization approaches that can be used for parameter setting for injection molding. These approaches includes Mathematical Modelling, Taguchi Method, Artificial Neural Network (ANN), Fuzzy Logic, case based reasoning and Genetic Algorithm (GA). They found Taguchi's optimization technique is one of the best and comparatively easy method to employ.

Chen, W. C., M. W. Wang, G. L. Fu, and C. T. Chen (2008) [17] presented a knowledge based system through data mining and analysis for determining optimal process setting parameters effectively. They have proposed a new hybrid optimization approach which integrates Taguchi's parameters design, Back-Propagation Neural Network (BPNN) and Davidon-Fletcher-Powell (DFP) method to optimize the process parameter setting more effectively in less time and also to obtain more reliable product quality.

S. E. S. Bariran and K. S. M. Sahari (2013) [18] have reviewed several optimization methods available and applications of those methods applied to different research objectives. They have concluded that Taguchi method combined with other heuristic methods such as Artificial Neural Network and Genetic Algorithm proves to be a better tool for optimization especially for material selection and mold design.

N. A. Shuaib et al. (2011) [19] analyzed a deflection due to warpage in a thin shallow injection molded plate of 0.5mm thickness. They have identified the five factors to be the parameters for their research. They are mold temperature, melt temperature, filing time, packing pressure and packing time. They have used Autodesk Moldflow Insight for performing simulation and then analyzed the results using Taguchi method. They have taken L16 orthogonal array and performed Analysis of Variance (ANOVA) to evaluate the significant processing factors. They found that the packing time has a highest contribution with 24.6 percentage and mold temperature is the lowest contributor with 15.7 percentage.

Wei Guo, Lin Hua, Huajie Mao and ZhenghuaMeng (2012) [20] analyzed a warpage in the automobile interior housing trim using FEA simulation and Design of Experiments (DOE). At first, they used a fractional factorial design of experiments (FFD). They proposed that FFD is suitable to arrive at the most influential processing parameters and their effects. L16 FFD array was used with 8 parameters and 2 levels. In next step, they have chosen 4 most influential parameters out of 8 and performed a central composite design of experiments (CCD) with 30 trials. They used a statistical software Minitab to analyze and plot response surface plots from results of CCD.

Shiqiang Zhang (2013) [21] employed analytical, numerical and experimental techniques to optimize filling time and gate of the injection mold on plastic air intake manifold of engines. He have used Lagrange quadratic interpolation for initial prediction filling time and respective injection pressure. Then he have done parametric simulations using moldflow software to optimize gate location and numbers of gates for minimum deflection due to warpage.

L.M. Galantucci and R. Spina (2003) [22]have integrated numerical simulations and experimental tests for evaluating injection conditions and processing parameters for plastic injection molding. Similar lines of other researcher, 5 process parameters viz. melt temperature, mold temperature, injection time, packing time and packing pressure were chosen to be variables. An L8 Taguchi design was planned for above five factors with two levels of each followed by the response surface. Response surface was built using the Box-Behnken Design (BDD) and six responses were selected viz. bulk temperature, shear stress, clamp force, sink index, volumetric shrinkage and linear shrinkage.

Baoshou Sun, Zhenfan Wu, GuBoqin, and Xiaodiao Huang (2010) [23] used Response Surface Methodology and combined it with Genetic Algorithm (GA) to optimize injection molding process parameters. They have selected same parameters as L.M. Galantucci but instead of Taguchi they have opted Latin Square DOE to build the orthogonal array, and according to Latin Square DOE 9 levels of each factor were chosen for experiments. Response Surface model was then combined with Genetic Algorithm to find the optimal process parameters.

Maria G. Villarreal, RachmatMulyana, José M. Castro and Mauricio Cabrera-Ríos (2008)[24] proposed a new simulation optimization method. As per their finding, it differs from the traditional approach in two ways: (1) at each iteration it uses all available information to build a metamodel that uses all degrees of freedom, and (2) as information is added through the progressive iteration of the method, it aims for a local fit.They have also tested their new method by performing experiment on a simple rectangular plaque of size 0.12m x 0.06m x 0.03m of Poly-styrene (PS). They have measured the shrinkage values along the four edges of plaque with different combinations of two controllable variables, Melt Temperature and Packing Pressure. They have also implemented the method on real automotive part Honda Civic rear bumper, in order to minimize variability in shrinkage. They have used mold temperature, melt temperature and three different injection locations as a variable parameters.

Maria G. Villarreal, RachmatMulyana, José M. Castro and Mauricio Cabrera-Ríos (2011) [25] have extended their previous research in simulation optimization and proposed a new multicriteria optimization method via simulation algorithm. They have illustrated their proposed method for optimization of shrinkage defect in injection molded disposable camera cover. For design of experiments they have used Central Composite Design (CCD) and Latin Hypercube Design (LHD) one with two and one with three performance measures for each design.

From above review, it is evident that researchers are successfully using finite element approach for optimizing injection molding parameters related to processing, product design and tooling. Researchers have used many Finite Element Simulation packages like C-MOLD, Moldflow Plastic Insight and Autodesk Simulation Moldflow for performing virtual trials. Autodesk Simulation Moldflow is one of the most common and reliable FEA package available for molding industry. But with the advancement in artificial intelligence, computer graphics and programming, many other newly developed and equally capable exclusive FEA softwares are available for Plastic Injection Molding industry like Simpoe mold, moldex3D, VISI flow, Sigmasoft etc. which are yet to be reviewed by the researchers. It is obvious that simulation technique combined with optimization techniques such as Design of Experiments, Taguchi Method, Analysis of Variance, Response Surface Method and Genetic Algorithm provides a better solution.

III. CONCLUSION

Because of the complexity of the injection molding process andinvolvement of large number of factors related to process settings, machine settings, product design and tool design, analysis and optimization of the Plastic Injection Molding becomes challenging. And as a result, many different tools and techniques have been developed and will be developed in futureto predict the defects in the molding and to optimize different parameters causing defects more precisely. It can be seen that optimization of plastic injectionmolding process using Finite Element Analysis (FEA) coupled with various optimization techniques is more economic and effective way in improving product quality and reducing manufacturing cost by saving costly trial and errors during design phase. There lies a future scope of conducting a more comprehensive parametric study of the injection molding process parameters using Finite Element Simulations and their interactions for optimizing the process using full factorial design of experiments so that one can get an exact solution. As well as with the new advance techniques in software development field, there is a future scope for integratingsuitable Design of Experiments (DOE) and optimization methods into Moldflow Simulation Softwares.

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