

Artificial Intelligence–Driven Real-Time Process Control for Consistent Quality in Injection Molding

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Abstract- The nature of complex interactions between machine, material and process parameters frequently leads to quality inconsistencies in injection molding processes. The present paper introduces an autonomous quality control framework based on AI and having real-time data on cavity pressure and temperature sensors of industrial injection molding cycles. Process data in large quantities are used to train learning models which learn to detect quality-sensitive cavity conditions and predict deviations which cause defective products. The system dynamically modifies the input parameters to the machine based on a real-time comparison with the learned reference patterns to stabilize in-cavity conditions. The feasibility of the proposed approach shows how AI-based control can help to ensure the stability of the quality of the products in the case of industrial injection molding. The framework employs an Artificial Neural Network (ANN)-based predictive model for real-time defect prediction and adaptive process parameter optimization.

Keywords-- Injection molding; Artificial intelligence; Real-time process control; Quality consistency; Cavity pressure; Cavity temperature; Machine learning; Smart manufacturing

1. INTRODUCTION

The injection molding is also among the most popular manufacturing technologies that are employed to produce the plastic parts in large scale with high productivity, dimensional accuracy, and repeatability. Modern development of moldinmachines and simulation machines have greatly minimized the occurrence of faults in the process [1]. Nevertheless, the growing demand of quality and flawless products keeps inflicting strict demands on the producers. Injection-molded components are determined by a complex interplay of machine, material and process parameters [2] and a poor choice of parameters may result in defects, including shrinkage, warpage, sink marks and dimensional errors [3] [4].

As shown in figure 1, it can be seen that to manage the process of injection molding, the design, real-time measurements, and constant monitoring of the key process variables are needed to guarantee their observability and controllability [5], [6]. Injection molding cycle involves four great steps namely plasticization, injection, cooling and ejection where the

cooling step consumes about 50-80 percent of the cycle time and has a predominating role in determining the quality and productivity of the product [7]. Despite the reported several optimization methods and simulation-based research on the identification of optimal process parameters, their application in practice faces the challenge due to the cycle-to-cycle variation, material variation, and environmental perturbation that lead to the variation in quality during the real production [8].

It was investigated by researchers that Artificial Neural Network (ANN) models can address this limitation by learning complex nonlinear relationships and enabling real-time prediction and adaptive control of process parameters.

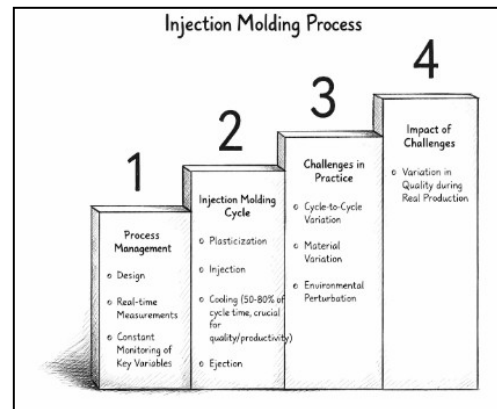


Figure 1: Stages of Injection Molding Process Control and Associated Quality Challenges

The current developments in process monitoring, variotherm molding, and conformal cooling methods have put emphasis on the possibility of applying artificial intelligence (AI)-based strategies to intelligent process control and quality assurance [9][10]. AI methods allow revealing the latent patterns in extensive data on the processes and provide the possibility to characterize the nonlinear interactions between the process parameters and quality characteristics in a more efficient way, compared to traditional procedures [11]. Although sensor-rich data acquisition systems and sensor-rich molding machines are available, quality control and troubleshooting in injection molding are still in large part left to operator experience and manual interventions [12].

Real-time quality control is a difficult concept to apply fully autonomously as the process is complex and multivariate in nature [13]. In this respect, the combination of the AI-based models and the big data analytics is an opportunity to use a consistent quality of products [14]. This paper aims to create and introduce an AI-based automatic quality control system of injection molding with respect to actual industrial manufacturing data of a car part. The proposed system will utilize data generated by the machine processes and smart learning algorithms to determine quality results and allow making decisions based on the data. The significant contributions of this work are: (i) the creation of a model of the use of AI in quality control in injection molding, (ii) the incorporation of big data analytics in working with extensive process data, and (iii) the presentation of the proposed solution in a real industrial process. The rest of the paper is structured in the following way: state-of-the-art studies review, research methodology, results and discussion, and conclusion remarks. State of the Art Over the last few years much variety of methods is reported on real-time monitoring and quality control in injection molding processes to minimize the usual defects, including warpage, shrinkage, sink marks, and flashes. Initial parameter optimization by classical model-based control and statistical tools including Taguchi techniques has been highly used, but is not effective in situations with nonlinear and dynamical behaviour of processes[15]. In order to overcome such shortcomings, the artificial intelligence methods such as Artificial Neural Networks (ANN), Fuzzy Logic, Genetic Algorithms (GA), Support Vector Machines (SVM) and Case-Based Reasoning have started to be actively investigated in terms of predicting and optimization of process parameters [16]. Data acquisition, data mining, and knowledge-based models have also been suggested to combine and create adaptive and self-learning process control frameworks to enhance robustness and repeatability [17]. There exist several studies which have reported the application of nozzle based and cavity based pressure and temperature sensor in monitoring real-time processes and fault detection [18]. Even though sensor based monitoring systems have now become widespread in industrial molding machines, the majority of the available systems are based on decision support and not autonomous control [19-20]. As machine learning and big data analytics have appeared, there is still a lot of room to create completely AI-based control systems in which the injection molding machine can learn based on historic and real-time data and automatically maintain the same quality of products [21-22].

Research Methodology This paper suggests an on-line monitoring, diagnostics and automatic quality control system of the injection molding process. The methodology commences with massive data creation of millions of cycles of molding with cavity pressure and temperature sensors as shown in Figure 2. A cycle is completed with sensor signals matched with matching cycle IDs, machine process parameters and quality outcomes of products by classification. The multi-source information that has been obtained is stored in a central

database where it can be further analyzed and a model obtained. The statistical and machine learning are used to examine the interconnection between the parameters of the process, the in-cavity, and quality of the product. Using these relationships, a compensatory control algorithm is created so as to dynamically modify the parameters of machine inputs to attain desired cavity conditions. The proposed system will allow correcting the processes autonomously and using the data in order to guarantee the production cycle with the same quality of the product.

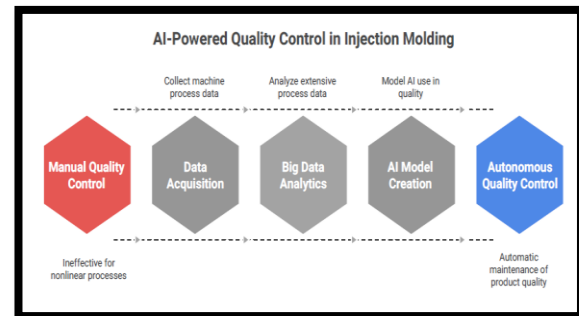


Figure 2: AI-Powered Workflow for Real-Time Quality Control in Injection Molding

2. DESCRIPTION AND DISCUSSIONS.

The systems proposed in this real-time monitoring and control system has two temperature sensors and two pressure sensors, which are built in the mold cavity of an automotive door module to measure in-cavity thermal and pressure behavior at the end of every molding cycle. Such sensor theorists give first hand knowledge on the actual molding conditions, which are highly dependent on the machine input parameters injecting pressure, holding pressure, mold temperature, and injecting speed. Although some of the parameters can be directly controlled using the machine controller, some can be indirectly controlled using the thermodynamic pressure-volume-temperature (PVT) behaviour of the polymer material. During the supervised learning period, the signature of cavity pressure and temperature is correlated with the quality outcomes of each product to determine the range of critical parameters that relate to part defects. The trained AI model will be comparing real-time sensor measurements with trained reference patterns and calculating deviations between the optimal cavity conditions. Depending on this deviation, the system emits compensatory machine input parameters to recuperate desirable in-cavity behavior. These are new parameters that are executed automatically on the machine controller. The entire data capture, model training, analysis and control logic is done in Python and a specific interface is designed which can be easily incorporated into the injection molding machine. The developed model, which is based on the information about millions of cycles allows quick adaptation and providing better prediction accuracy which allows the compensation of process interferences in real time and provides the product with the same quality.

3. CONCLUSION

There are still challenges in ensuring that the products remain of a consistent quality because of the variance in cycles to cycle and intricate interaction between machine, material and process parameters in injection molding. This paper shows that in-cavity pressure and temperature sensor-based real-time monitoring of the process can inform about the real-life situation of molding. Reference models and control strategies may be generated by gathering and evaluating data regarding millions of molding cycles to connect sensor indicators with machine input parameters and quality of products. The suggested AI-driven model allows learning the quality-sensitive cavity conditions with supervision and provides the possibility to compensate it in real time by automatically changing the settings of the machine. The AI-based control is more flexible, stable, and stable than traditional methods of quality control. The findings indicate the promising opportunities of autonomous quality control systems in maintaining production consistency in industrial injection molding. The next step in work will be the refinement of the learning algorithms, a large-scale implementation of the learning algorithms on the automotive components, and experimental confirmation of the proposed system in the real-life manufacturing conditions.

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