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Impact of Process Parameters on Cycle Time of Rubber Injection Molding Process - A Review

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ABSTRACT

Rubber injection molding is an advanced manufacturing process used to produce high quality and precise rubber products by injecting rubber material into a heated mould under pressure. It is widely used across industries for its efficiency, excellent dimensional accuracy, and ability to manufacture complex rubber parts with minimal waste. Cycle time in rubber injection moulding refers to the total time required to produce one finished rubber part, from material injection to curing, cooling, and ejection. This present literature review examines how cycle time behaves in rubber injection moulding along with the properties of rubber compounds. Rubber injection moulding is an important manufacturing process, and cycle time strongly affects both productivity and production cost. The review looks at how different process parameters influence cycle time during rubber processing. It also underlines the role of curing time, mould temperature, and material characteristics in improving overall efficiency. Along with this, the physical and chemical behaviour of rubber compounds and its impact on moulding performance are also discussed in this research paper. It is generally observed that better control of process parameters leads to improved product quality. The review also identifies the main factors responsible for variations in cycle time in rubber injection moulding.

Keywords- Injection Molding, Rubber Molding, Cycle Time, Mould Parameters.

I. INTRODUCTION

Cycle time plays a significant role in the injection moulding process, including the quality of the parts produced, but especially the impact it makes on a company's financial bottom line. Rubber injection molding is a repetitive manufacturing process in which production cycle consists of feeding the rubber compound, plasticizing and homogenizing it in the injection barrel, closing the mold, injecting the material into the mold cavity under pressure, curing the rubber through heat, opening the mold, and ejecting or removing the finished component [1-2]. The flow behavior of rubber compounds is one of the key challenge in rubber injection molding considerable different from that of thermoplastics. The rubber compounds must be injected within a limited temperature range of approximately 70–110 °C to avoid premature vulcanization while maintaining sufficient flowability [3].

Once the processing parameters of injection molding machine have been established, the quality of the final product is largely determined by the characteristics of the rubber compound, which are influenced by processing temperature, pressure, and time. Among these variables, temperature is particularly critical because increasing the rubber temperature during injection decreases its viscosity and enhances flowability. However, if the temperature rises beyond the optimal range, premature curing may begin during the filling stage, resulting in a rapid increase in viscosity that impedes or completely stops the flow of the rubber within the mold [4].

In industrial practice, process control is typically achieved through the adjustment of machine parameters and laboratory testing of compounds prior to production, as well as the inspection and removal of defective parts after production. However, online monitoring systems could enable real-time modification of machine settings at the earliest signs of defect formation, thereby reducing the delay between defect occurrence and the implementation of corrective actions [5-7].

The various types of rubber that can be moulded include natural rubber, as well as synthetic rubber such as neoprene, foam rubber, EPDM, silicone rubber, and liquid silicone rubber. When undergoing a molding process, it is important to choose the correct compound and manufacturing process to achieve the desired end result. By choosing the right kind of molding process for your application, you are ensuring optimum performance levels and cost effectiveness. This paper presents the various research work done in the area of development of products by rubber injection moulding and it's processing parameters.

II. LITERATURE REVIEW

Hans-Joachim Graf [8] compared rubber injection moulding with compression and transfer moulding and highlighted the advantages of injection moulding over the other two processes. He also proposed a strategy for applying this knowledge to establish the process in a way that is largely independent of the machine used. This was achieved by integrating the concept of an operating window in injection moulding with statistical experimental design techniques. Karthik G. L. et al. [9] presented a conceptual design of a rubber injection mould in their study. The authors developed three different two-plate mould concepts for evaluation. The material used was EPDM, and the mould temperature was controlled using a SELEC TC513 temperature controller. In their work, three configurations were designed, including a single-cavity concept, a four-cavity concept, and a finger-cam actuation concept. The results indicated that the finger-cam actuated mould was capable of producing quality parts at a comparatively lower cost. It was also observed that maintaining mould temperature through the SELEC TC513 controller played an important role during the curing stage. The study further highlighted that precise control of process parameters such as barrel temperature and mould temperature is essential for achieving consistent product quality.

Michal Stanek et al. [10] conducted a simulation-based study on the injection moulding of rubber compounds. They emphasized that rubber compounds can be calculated and analyzed during the design stage of production preparation to achieve better results; however, their conclusions were primarily applicable to thermoplastic parts. The study reported that at a curing time of 208 seconds, the average material temperature across the wall thickness was determined. The authors suggested that injection moulding of rubber compounds can be more effectively optimized through analytical calculations rather than a trial-and-error approach. They also concluded that curing time is influenced by the minimum and maximum percentage of vulcanized bonds formed during the process.

Vishnuvardhan M. et al. [11] carried out a study focused on cycle time optimization using Moldflow analysis. For their investigation, a Hinge Locator component was selected, and multiple simulations were performed using Moldflow software to study and reduce the cycle time. The results showed that, by applying the process parameters recommended by Moldflow, the cycle time could be reduced significantly from 35 seconds to 24 seconds. The key parameters influencing this reduction included the proper location of the gate and runner system, along with appropriate melt temperature settings at a given cycle time. Muhammad Khan et al. [12] carried out an experimental investigation on cycle time reduction using a robust cooling channel design, specifically conformal cooling channels. Their study demonstrated that a reduction in cooling time can be achieved through uniform temperature distribution within the moulded part, which is facilitated by conformal cooling channels. The results showed that the cooling time was initially 15.63 seconds, which was reduced to 14.63 seconds using the conformal cooling channel design. Further improvement was achieved by introducing an additional cooling line, reducing the cooling time to 14.13 seconds. Overall, a total reduction of approximately 1.5 seconds was achieved from the initial cycle time.

Satoshi Kitayama et al. [13] investigated the use of conformal cooling channels to reduce cycle time and minimize warpage. In their study, the conformal cooling channels were fabricated using additive manufacturing techniques. Their results indicated that the mould temperature obtained through numerical simulation was set at 90 °C. The effectiveness of the conformal cooling design was evaluated through both numerical and experimental approaches. Based on their findings, they recommended a mould temperature range of 60–120 °C and a melt temperature range of 180–210 °C. It was concluded that operating within these temperature ranges can help reduce cycle time while avoiding warpage issues.

Munendra Koli [14] collected experimental data from an IIM Milacron injection moulding machine and carried out statistical analysis to optimize cycle time and provide recommendations for process improvement. The study focused on understanding methods to reduce cycle time, identifying possible optimization approaches, and evaluating the key factors that influence it. It was noted that achieving improved productivity and quality is a primary goal in any manufacturing process. In injection moulding, if part design, mould design, and mould precision are properly controlled, defect-free production with optimized cycle time can be achieved. The study used polypropylene components with a wall thickness of 0.3 mm. The findings revealed that cooling time accounted for the largest portion of the overall cycle time. Therefore, multiple iterations were performed to determine an optimal cooling time without introducing defects. The optimum cooling time was found to be 7.5 seconds, resulting in an overall cycle time of 17.5 seconds. The results demonstrated a practical and cost-effective approach to cycle time optimization in injection moulding.

K. Kyas et al. [15] conducted a study to measure temperature and pressure during elastomeric injection moulding using CADMOULD for rubber simulation software. The study compared real-time data obtained from temperature and pressure sensors in the actual process with results from computational flow analysis. The findings indicated that combining sensor data with simulation results can be highly beneficial for the polymer and rubber industry, as it helps in optimizing process settings and reducing the overall production cycle time. It was also suggested that the use of sensors along with flow analysis provides a more accurate basis for process optimization. According to Kyas, the crosslinking behaviour of elastomeric compounds depends on temperature, pressure, and time. Therefore, the vulcanization time can be reduced by appropriately adjusting process parameters such as temperature and pressure.

Roberto Spina [16] investigated PE/EVA foam injection molded parts, using finite element analysis to assess parameters influencing several aspects, such as foam morphology and compression behaviour. For this purpose, he used polymeric blend consisted of a mixture of low-density polyethylene (LDPEs), a high-density polyethylene (HDPE), an ethylene-vinyl acetate (EVA) and an azodicarbonamide (ADC). The thermal, rheological and compression properties of the blend are fully described, as well as the numerical models and the parameters of the injection molding process. The flow front advancements of un-foamed and foamed blend were computed as well as the part density, consequently allowing the evaluation of the effects on mechanical characterization. The research has overcome limitations related to the fact that most of the work performed was related to a single foam without considering the finer implications on the property and modelling of the blend. He concluded that the temperature was found to be the main influencing factor through the DSC and rheological analyses while the shot volume was identified after compression tests on foamed products.

Chil-Chyuan Kuo et al. [17] studied the effects of different filler on silicon rubber mold while using conformal cooling channel. The cooling performance in the cooling stage is not acceptable after the injection molding due to low thermal conductivity of this material. For the experiment the filler used was graphite, aluminium, black powder. Normally, SR was used as matrix materials for the fabrication of thermally composites, they used different fillers and Conformal Cooling Channel to obtain optimal cooling time. It was found that the alcohol used to remove the polyvinyl butyral resin cooling channels is less volatile, environmentally friendly, and less harmful to the operator compared with conventional method using acetone to remove the acrylonitrile butadiene styrene cooling channels. As the result they found out that the SR filled with 20 wt.% Graphite powder seems to be the optimal method for producing a silicon rubber mold (SRM) with better cooling performance based on the thermal conductivity, production cost, and production yield of SRM.

Roberto Spina [18] carried out the study to predict the microstructure of final part component by blending PE/EVA with two types of ADC foaming agents using differential scanning calorimetry and rotational rheometric. The results point out that the use of the blend with type one ADC leads to a greater porosity and better coloration of the part, with a consequent reduction in the part weight, while type 2 ADC, characterized by a lower decomposition temperature range, allows better pore distribution to be achieved.

Saad Mohamed Suleiman Mukras [19] conducted an experimental based study for short the cycle time and their relation with the defects namely volumetric shrinkage and warpage of injection molding process with the help of certain process parameters. He considered seven process parameters including injection speed, injection pressure, cooling time, packing pressure, mold temperature, packing time, and melt temperature. Then created three relationships between the product cycle time (one relationship), the two product defects (two relationships), and the injection molding parameters were constructed using the kriging technique. Results from the additional experiment showed reasonably close agreement with simulation optimization results differing in the cycle time, the warpage and volumetric shrinkage by 6.7%, 3.2%, and 8%, respectively. He also concluded that Cooling time and the packing time have the opposing effect of increasing the cycle time while reducing the product defects and secondly that the injection pressure, the mold temperature and the melt temperature have a supporting effect of lowering the product cycle time while lowering the product defect.

K. Kamarudin et al [20] describes the growth of Solid Free Form Technology (SFF) that allows the mould designer to develop more than just a regular conformal cooling channel. Numerous researchers demonstrate that conformal cooling channel was tremendously given significant result in the improvement of productivity and quality in the plastic injection moulding process, his Study focused in square shape cooling channel to enhance the efficiency of cooling performance by adding the sub groove to the cooling channel itself using 8 designs to improve the cycle time for plastic injection molding. For this purpose, he included sub-grooves to the cooling channel design and through this this study, he found that 8 sub-groove profile was the best design to enhance the heat transfer rate. The addition of sub-groove number will increase the cooling channel perimeter and the contact surface area due to the heat convection.

Kailas R. Dudhe [21] tried to reduce cycle time of injection molding with the help of thermal analysis. The author explained that cycle time reduced through various techniques like external cooling, improve capacity of cooling tower, Install Flow Meters, Proper design of the cooling channel, Optimization of Injection Molding Machine Parameters like Cooling Time, Back Pressure and Plasticizing Limit, Optimum Height for Counter Flow Cooling Tower. Through thermal analysis it was concluded that high and low levels for cooling time was 5 and 15 seconds, plasticizing limit was 70 and 88 mm, and back pressure was set at 5 and 17 bar. The proposed design cycle time is improved and heat uniformly is increased. Long Jing et al. [22] analysed the cooling technique using heat pipe. He used CFD software ICEPAK in the report to make a numerical simulation as well as a simulation analysis of the Heat pipe cooling scheme. The two schemes were Heat pipe bending cooling scheme & Heat pipe cooling scheme and compared two kinds of cooling mode using heat pipe cooling system to solve the heat dissipation problem. With the help of thermal analysis, he concluded that the heat pipe cooling fin dissipates heat in electronic products has great advantages and, the arrangement of the fins exerts little effect on the cooling effect.

Sulas G.Borkar et al. [23] carried out the experiment and observations were taken with conventional water jacket method and heat pipe system. Injection moulding and die casting moulds are the basic casting methods which are cooled with conventional water jacket method. Cooling of mould is essential in order to obtain the good quality of moulded part. Further the factor which is also absolutely essential is the rate of production. Conventional water jacket method is not suitable to obtain the good results and possess many disadvantages. Hence heat pipes are used in conventional water jacket method to cool the molding processes. They compared the result from conventional water jacket method and heat pipe cooling technique. They observed that the liquid cooling with heat pipe system is more effective than liquid cooling with conventional water jacket method. With this experiment they concluded that liquid cooling with heat pipe system is 2.25 times effective than liquid cooling with water jacket method.

Mrozek K. et al. [24] conducted study on results of injection mold cooling system research for cooling efficiency of molding used in electric and electronic industry. The component used was PA 6.6 with trade name of FRIANYL RV0 GN A63 for electrical connector casing. The result they found out that the cooling efficiency increasing follows with decreasing of distance between cooling channels and cavity surface. The increasing of the cooling channels diameter for small-sized moldings has a little effect on the rate of cooling and may have an adverse effect on the uniformity of the process. When considering the injection process of cold channel injection system is not possible to optimize the cooling process. Donggang Yao et al. [25] developed a rapid heating and cooling system for injection molding units. In this paper he investigated to solve the problem associated with constant temperature mold, the rapid heating and cooling systems consisting of one metallic heating layer and one oxide insulation layer used. For that purpose, they developed a mold capable of raising temperature from 25°C to 250°C in 2 seconds and cooling to 50°C within 10 seconds. With this research the optimal insulation thickness with respect to the minimal cycle time was found to be 0.5 mm. Cycle time simulation of 4-mm-thick polycarbonate samples showed that 30% of the conventional cycle time is saved by using a rapid thermal response mold. To achieve a temperature-rise from 25°C to 250°C in 2 seconds, a power density of 50 W/cm2 or above was found to be necessary.

R. Sanchez et al. [26] in their paper introduced the mold temperature curve to realize how Rapid Heating and Cooling Mold works, and compare its results with conventional molding to understand the surface temperature by rapid heating the injection molding unit. In this study, an electrical power system was made, for a testing part injected with two amorphous polymers under conventional and rapid heating and cooling systems. The thermal results showed that the variation of surface mold temperature during the injection cycle offers a set of new possibilities of process control, including the excellent appearance that this new technology exhibits and the improvement of weld line strength. R. D. Allen et al. [27] conducted a study on the expansion property of EVA after curing. EVA has the remarkable ability to expand between 30% and 90% compared to the injection mold size, depending on the amount of blowing agent added. To understand this, they conducted, Design of experiment methodology and Cavity prediction methodology. For the study of EVA expanding property, he chose evlax of grade EVLA. A methodology utilizing morphing technology has been defined for intelligent mold design and they explained that the expansion occurs in components with sections over 10mm thickness relative to the material expansion ratio and also found that thicknesses below 10mm produce unusual effects.

Schneider E. L. [28] tried to understand the non-uniform expansion behavior of injected EVA, the author conducted virtual analysis and compared it with analysis made with electron scanning microscope (SEM) by doing the sectioning of the sole. From this research they proved that in regions of smaller thickness and lower volume, the EVA blender expander cannot have its total expansion, i.e., the micro-bubbles of gases generated at the moment of expansion are smaller in these regions when compared with regions of greater volume and thickness. Yi-Ren Jeng et al. [29] tried to predict the expansion ratio of EVA Foam material for shoe sole with the help of FEM simulation. For that they done Experimental Design to Correlate the Temperature-time Curve with Expansion Ratio and Using Heat Expansion Theory to Simulate the Foam Expansion Behaviour. By comparing the result obtained by virtual analysis and practical analysis, they found that that there was maximum error is 0.54mm in the y direction which meets the requirement of shoe soles i.e., 3mm in the y-direction.

Chil-Chyuan Kuo et al. [30], in their study utilized Rapid Tooling technology to make a mold with a heating element for LSR injection molding. The mold was fabricated from aluminum-filled epoxy resin and injection could be done after a mold warm-up time of 35 min to stabilize mold surface temperature. The optimal process parameters were found to be: injection speed 50 mm/s, packing pressure 14 MPa, mold temperature 180°C, and packing time 12 s. Adam Skrobak et al. [31], attempted to evaluate and compare the physical properties i.e., tensile strength and tear strength of EPDM rubber obtained from injection molding and standard method of cutting out from compression molding. From the result they got that the injection molded material had higher strength than standard method. But the curing time had difference of about 5.9% which within optimum range.

K. Kyas et al. [32], attempted to understand the influence of runner on curing rate, for that purpose they used NBR rubber compound. In this paper they used CADMOLD for simulation analysis for understanding the curing time due to runner in REP V27/Y125 injection molding machine. They design types of runners i.e., circular and trapeze to conduct this experiment. It was found out that the optimal time for vulcanization was T=170 ºC. Optimum percentage of vulcanization was 90% in curing. J. L. Valentin et al. [33] investigated the uncertainty involved in determining cross-link density in natural rubber using equilibrium swelling experiments. Although this method is widely used and considered practical, the study noted that the obtained values can often be uncertain and, in some cases, inaccurate. The thermodynamic behaviour of swollen polymer networks is commonly described using the Flory–Rehner model. However, experimental observations suggest that both the Flory–Huggins mixing term and the elastic component based on the affine model are only approximations, and they do not fully capture or predict the actual behaviour of rubber networks. As a result, the Flory–Rehner approach provides only a qualitative estimation of cross-link density due to its strong dependence on the underlying thermodynamic assumptions. The study concluded that swelling experiments mainly offer an approximate indication of cross-link density, particularly for highly cross-linked samples. In contrast, multiple-quantum NMR (MQ NMR), even when performed using low-field instruments, was identified as a simpler and more reliable alternative for directly measuring cross-links and topological constraints in rubber systems.

Mohammad Abou Taha et al. (2021) [34] carried out an experimental study on crosslinked elastomers using a combination of established and advanced characterization techniques. Their work included macroscopic methods such as rheological and mechanical testing, along with equilibrium swelling measurements. In addition, they employed proton multiple-quantum NMR and in situ tensile X-ray scattering to evaluate stress-induced segmental orientation. By integrating these techniques, the authors examined unfilled sulphur-vulcanized styrene–butadiene rubber elastomers with varying degrees of crosslinking. This approach allowed them to analyse the response of the elastomer network in relation to its crosslinking structure. The study concluded that temperature plays a key role in rubber elasticity, particularly in relation to the stress–optical law and the behaviour of reinforced elastomers. According to rubber elasticity theory, the average chain orientation parameter is expected to remain independent of temperature, a behaviour that was also observed in reinforced materials.

III. CONCLUSION

This paper provides an overview of a number of recent breakthroughs in rubber injection molding process. Several studies on optimization techniques for reducing cycle time have also been investigated. The review includes both software-based and experimental approaches used for improving molding performance. It is commonly observed that improved control over process parameters results in better product quality. In addition, the key factors that contribute to variations in cycle time in rubber injection moulding have been identified.

FUTURE SCOPE OF WORK

The future work can focus on extending the study to different types of rubber materials to better understand their influence on cycle time in injection moulding. Further investigation is required to evaluate how various rubber compounds behave under different processing conditions. In addition, more research can be carried out on methods to reduce the curing time of rubber compounds without affecting product quality. Optimization of process parameters and advanced simulation techniques may also be explored to achieve further improvement in cycle time reduction.

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