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“INJECTION MOULD DESIGN FOR RIBBED AUTOMOTIVE AND FURNITURE PLASTIC COMPONENTS: A REVIEW OF GATE LOCATION, COOLING CHANNEL DESIGN, WARPAGE CONTROL, AND MACHINE SELECTION”

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ABSTRACT

Injection moulding is one of the principal processes for the mass production of plastic components used in the automotive, furniture, electrical, and consumer-goods industries. The quality, dimensional accuracy, and productivity of an injection-moulded part depend not only on the plastic material and the process parameters but, to a large extent, on the design of the mould, including the core and cavity, parting line, gate and runner system, cooling arrangement, ejection system, mould plates, and the selection of the injection moulding machine. Ribbed, thin-walled components such as armrest bases and other supporting parts are particularly demanding because ribs, holes, and rounded corners affect filling, cooling, shrinkage, and ejection. This review paper presents an assessment of published research and established practice relevant to the design of injection moulds for such components, with emphasis on gate location, cooling-channel design including conformal cooling, warpage and shrinkage control, mould structure and thermal behaviour, and the preliminary selection of machine clamping force and injection capacity. Studies on automotive armrest moulding, gate location, cooling systems, thermal analysis of moulds, warpage factors, process-parameter optimization, and conformal cooling design are examined. The review indicates that gate position and cooling layout strongly influence filling, temperature distribution, and dimensional stability, that conformal cooling and parameter optimization can improve cooling rate and reduce warpage, and that most studies address either simulation of a given part or a single design aspect, with comparatively few providing an integrated, component-specific treatment from product study through mould layout and machine selection. Research gaps are identified, including limited component-specific integration of mould design and engineering calculations, limited reporting of preliminary machine-selection procedures, and the need for validation of CAD-based designs by simulation and moulding trials. The findings are intended to support the design of reliable injection moulds for ribbed plastic components used in automotive and furniture applications.

Key Words: Injection mould; plastic injection moulding; gate location; cooling channels; conformal cooling; warpage; clamping force; mould design; armrest..

I. INTRODUCTION

Plastic components are used extensively in modern industry because they are lightweight, have a good strength-to-weight ratio, resist corrosion, and are inexpensive to produce in large numbers. They find application in the automotive and furniture industries, electrical appliances, medical devices, and consumer and household products. Injection moulding is the primary technology for the mass production of plastic parts: molten plastic is injected under pressure into a closed mould, where it takes the shape of the cavity and solidifies on cooling; the mould is then opened and the part is removed with the help of an ejector system [1]–[3]. The quality of the moulded component depends on the

product design, mould design, material selection, injection pressure, cooling arrangement, ejection system, and process accuracy, so careful mould design is essential for good dimensional accuracy, surface quality, repeatability, and production efficiency [2], [4].

The process consists of feeding plastic granules into the heated barrel of the machine, melting them by heat and screw rotation, injecting the melt through the sprue, runner, and gate into the mould cavity, cooling the part, opening the mould, and removing the component. A mould consists essentially of a fixed half, attached to the stationary platen of the machine, and a moving half, attached to the moving platen, with the cavity and core located between them. After cooling, the mould opens at the parting line and the part is ejected from the moving half. A typical mould comprises top and bottom clamping plates, cavity and core plates, spacer blocks, ejector and ejector retainer plates, guide pillars and bushes, and the runner, cooling, and ejection elements [3], [4]. A well-designed mould reduces defects, material wastage, cycle time, and maintenance problems, whereas a faulty design may cause incomplete filling, flash, sink marks, warpage, dimensional variation, improper cooling, ejection difficulty, surface imperfections, and long cycle times.

Components such as armrest bases, chair backs, handles, supports, and covers are produced from plastic in large quantities. These parts commonly include curved edges, through holes, thin walls, and ribs that provide stiffness without excessive material, and each of these features affects the mould design. Holes require core pins or inserts, ribs influence filling, cooling, and ejection and may cause sink marks if too thick, thin walls increase flow resistance, and rounded corners influence flow and cavity machining [4]. In addition, the mould must be matched to an injection moulding machine with sufficient clamping force and shot capacity, and the preliminary estimation of these values is usually the first quantitative step in mould and machine selection [1], [5]. This paper reviews the literature on these aspects, with the aim of identifying good practice for the design of injection moulds for ribbed plastic components and of highlighting the gaps that remain.

II. PROBLEM IDENTIFICATION

Moulding a plastic component with ribs, holes, and rounded edges requires that the mould be designed in accordance with the geometry of the part, the moulding direction, the parting line, the position of the core and cavity, the gate and runner system, the cooling system, and the ejection arrangement. If the mould is not designed properly, the cavity may not fill completely, weld lines may form near holes and ribs, cooling may be non-uniform, the product may warp, ejection may be difficult or may damage the part, the core and cavity may be misaligned, the surface quality may be poor, and the moulding cycle may be unnecessarily long. These problems affect product quality, mould life, and production cost.

A further difficulty is that the available literature is distributed across a number of specialized topics. Some studies investigate the effect of gate location on filling and cooling, others investigate cooling-channel design or conformal cooling, others warpage and shrinkage, and others provide reviews of the process. Few of them treat the design of a mould for a specific component in an integrated way, from product study and material selection through core and cavity layout, plate selection, engineering calculations, and machine selection. In addition, the final plastic grade, shrinkage, injection pressure, and cooling-channel layout are often not known at the early stage of design, so designers must rely on preliminary estimates, such as projected-area-based clamping force and shot-weight-based injection capacity, whose basis and limitations are seldom documented.

Consequently, there is a need to consolidate the available knowledge on gate location, cooling design, warpage control, and mould and machine selection, and to identify where the existing evidence is insufficient for the design of moulds for ribbed plastic components used in automotive and furniture applications. This review addresses that need.

III. RESEARCH OBJECTIVE

The main objective of this review paper is to critically examine published research and established practice related to the design of injection moulds for ribbed plastic components. The specific research objectives are as follows:

- To review the injection moulding process and mould construction: Describe the principal elements of an injection mould and the factors that determine moulded-part quality.
- To examine gate location: Review the influence of gate position on polymer flow, filling pattern, temperature distribution, and defects such as weld lines.
- To evaluate cooling-system design: Review the effect of cooling-channel arrangement, including conformal cooling channels, on temperature distribution, cooling time, and part quality.
- To analyze warpage and shrinkage: Examine the factors that cause warpage and the process-parameter optimization methods used to reduce warpage and shrinkage.
- To review mould structure and thermal behaviour: Examine the requirements for mould plates, core, cavity, guide elements, and ejection components under injection pressure and repeated loading.
- To assess preliminary machine selection: Review the use of projected area, clamping-force factors, shot weight, and design margins in the selection of an injection moulding machine.
- To identify research gaps: Identify limitations in existing studies relevant to the integrated, component-specific design of moulds for ribbed plastic components.

IV. LITERATURE REVIEW

The design of injection moulds is supported by standard handbooks and by research on mould filling, cooling, warpage, and process optimization. The studies reviewed below were published between 2001 and 2024 and are grouped by topic. For each study the scope and principal findings are summarized as reported by the authors, and its relevance to the design of a mould for a ribbed plastic component is highlighted. Where a study concerns a different product or a different cooling concept, this is stated, and its results are not assumed to apply directly to the component of interest.

Automotive armrest moulding. Park and Lee (2019) [6] investigated the injection moulding and in-mould coating process of an automotive armrest component. Their study considered the flow behaviour of the plastic and the coating process, analysed the moulding process, and compared the predicted results with experimental observations. The study showed that mould design and processing conditions have a significant effect on the filling behaviour and surface quality of an automotive armrest. It is relevant to armrest-type components, although the product geometry, material, and mould arrangement differ from those of other armrest parts.

Gate location and cooling. Hassan, Régnier, and Defaye (2009) [7] studied the effect of gate location on the cooling of polymer components during injection moulding, using a three-dimensional approach to relate gate position, polymer flow, and temperature distribution in the cavity. They reported that gate location influences both the filling pattern and the cooling behaviour of the polymer, and that improper gate positioning may produce non-uniform temperature distribution, weld lines, dimensional variation, improper filling, and localized cooling problems. Hassan et al. (2009) [8] investigated the effect of the cooling system on polymer temperature and solidification, focusing on heat transfer between the mould, cooling medium, and polymer. They highlighted that the cooling-channel arrangement has an important effect on temperature distribution and solidification time, and that uneven cooling may result in differential shrinkage, warpage, dimensional inaccuracy, a longer cooling time, and poor product quality. Together, these studies indicate that the gate position must be selected according to the geometry, wall thickness, and functional requirements of the part, and that the cooling provisions around the core and cavity should provide uniform heat removal without weakening the mould plates.

Mould structure and thermal behaviour. Tang et al. (2006) [9] studied the design and thermal analysis of a plastic injection mould. Their work discussed the structural arrangement of the mould components and the thermal behaviour during the injection moulding cycle, and it indicated that the mould must be designed to withstand injection pressure and repeated loading. The proper selection of mould plates, core, cavity, guide elements, and ejection components is

necessary for safe and reliable operation. The study is directly relevant to the design of a mould base consisting of clamping plates, core and cavity plates, ejector plates, spacer blocks, and guide elements.

Warpage and shrinkage. Huang and Tai (2001) [10] investigated the factors affecting warpage in an injection-moulded part with a thin-shell feature, considering the influence of product geometry and processing conditions on the deformation of thin plastic parts. They reported that warpage is mainly associated with non-uniform shrinkage, unequal cooling, residual stresses, improper processing conditions, and variation in wall thickness, which shows that product design and mould design are both important in controlling deformation. Zhao et al. (2022) [11] reviewed recent progress in minimizing warpage and shrinkage through the optimization of process parameters such as pressure, temperature, injection rate, and cooling and holding time. They concluded that several interacting factors influence warpage and shrinkage and that systematic optimization improves dimensional reliability. Yang et al. (2022) [12] studied the optimization of injection-moulding parameters for a plastic automotive front-end frame, focusing on the interdependence of process parameters, warpage, and shrinkage, and confirmed the significance of correct parameters for the dimensional accuracy of plastic automotive components.

Conformal cooling channels. Rahim et al. (2016) [13] investigated a new design of conformal cooling channels to improve the quality and productivity of moulded parts. Conformal channels follow the shape of the cavity more closely than conventional straight channels and, in the study, improved cooling-channel design reduced temperature variation and improved the quality of the moulded parts, with potential benefits of shorter cooling time, better temperature uniformity, reduced warpage, and improved efficiency. Shinde and Ashtankar (2018) [14] compared different conformal cooling-channel shapes and their influence on cooling performance and moulding-cycle parameters, demonstrating that channel geometry is an important design variable and that different configurations produce different outcomes. Torres-Alba et al. (2020) [15] proposed a cooling-channel design procedure based on temperature clusters and multidimensional discrete models, aimed at developing channel patterns that depend on the structure of the moulded part and its temperature requirements, and showed the effectiveness of the approach. Nguyen et al. (2023) [16] developed a design approach for conformal cooling channels to improve the temperature distribution on the cavity surface, analysing channel configuration and applying a systematic optimization technique. Li et al. (2024) [17] examined the optimization of conformal cooling channels to increase the cooling rate, supporting cooling-channel geometry as a key factor in mould performance. These studies show that cooling-channel design can substantially influence temperature uniformity and cooling rate, but they generally concern specific parts and concepts and cannot be assumed to apply directly to another component without further evaluation. Moreover, conformal channels typically require advanced manufacturing, so a conventional channel layout may be chosen where such facilities are not available.

Process reviews. Farooque, Asjad, and Rizvi (2021) [18] reviewed current developments in injection-moulding manufacturing processes, discussing the importance of mould design, material selection, process parameters, and production control. The review highlighted that injection pressure, injection speed, melt temperature, mould temperature, holding pressure, cooling time, material selection, and gate design affect the quality of the final component and must be controlled to reduce defects and improve productivity. General process reviews, however, do not by themselves provide the complete mould design for a selected component.

Table 4.1: Summary of the reviewed studies

Study	Focus	Relevance to mould design
Park and Lee (2019) [6]	Moulding and in-mould coating of an automotive armrest	Armrest-type component; filling and surface quality
Hassan et al. (2009) [7]	Gate location and polymer cooling	Gate position, weld lines, filling pattern
Hassan et al. (2009) [8]	Cooling system and solidification	Cooling layout, shrinkage, warpage
Tang et al. (2006) [9]	Mould design and thermal analysis	Mould plates, core, cavity, ejection
Huang and Tai (2001) [10]	Warpage of thin-shell parts	Wall thickness, shrinkage, cooling
Zhao et al. (2022) [11]	Warpage and shrinkage optimization review	Process parameters and dimensional accuracy
Yang et al. (2022) [12]	Automotive front-end frame parameters	Automotive plastic component
Rahim et al. (2016) [13]	Conformal cooling channels	Temperature uniformity, productivity
Shinde and Ashtankar (2018) [14]	Cooling-channel shapes	Channel geometry as design variable
Torres-Alba et al. (2020) [15]	Cooling design procedure	Part-specific channel layout
Nguyen et al. (2023) [16]	Cavity-surface temperature distribution	Temperature uniformity
Li et al. (2024) [17]	Cooling-rate optimization	Channel geometry and cooling rate
Farooque et al. (2021) [18]	Process review	Process parameters and gate design

Summary and research gaps. Several themes emerge from the reviewed work. First, gate location and cooling-channel arrangement strongly influence filling, temperature distribution, and solidification, and they should be selected according to the product geometry, wall thickness, and functional requirements [7], [8]. Second, warpage is associated with non-uniform shrinkage, unequal cooling, residual stress, process conditions, and wall-thickness variation, and it can be reduced by suitable product and mould design and by optimization of process parameters [10]–[12]. Third, conformal cooling and optimized channel geometry can improve temperature uniformity and cooling rate, although the results are specific to the parts and concepts studied [13]–[17]. Fourth, the mould structure must withstand injection pressure and repeated loading, which requires suitable plates, guide elements, and ejection components [9]. Finally, the reviewed studies mostly concern a specific simulation or a single design aspect. Few provide a component-specific integration of mould layout, core and cavity design, gate and runner concept, cooling, ejection, engineering calculations, and preliminary machine selection, and the relevance of some studies to a given base-plate geometry has to be established separately. These observations define the gap addressed by component-specific design studies.

V. CONCLUSION

This review examined published research and established practice related to the design of injection moulds for ribbed plastic components used in automotive and furniture applications. The literature indicates that mould design strongly influences the quality, dimensional accuracy, and productivity of moulded parts. Gate location affects filling pattern, weld lines, and cooling, while the cooling-channel arrangement controls temperature distribution, solidification time, shrinkage, and warpage; conformal cooling and optimized channel geometry can improve cooling performance, and optimization of process parameters can reduce warpage and shrinkage. The mould structure, including the clamping plates, core and cavity plates, spacer blocks, and ejector plates, must be able to withstand injection pressure and repeated loading, and the injection moulding machine must be selected on the basis of clamping force, which depends on the projected area, and injection capacity, which depends on the shot weight, with suitable design margins. Future research should integrate product study, mould layout, engineering calculations, and machine selection for specific components, document the basis of preliminary estimates such as clamping-force factors and runner allowances, and validate CAD-based mould designs by flow and thermal simulation and by moulding trials. Addressing these gaps can support the development of efficient and reliable injection moulds for ribbed plastic components.

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