UDC 666.1.001.7 doi:10.20998/2413-4295.2025.01.12

COMPREHENSIVE ANALYSIS OF AUTOMOTIVE GLASS PRODUCTION: CHALLENGES, DEFECTS, AND QUALITY MANAGEMENT STRATEGIES

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ABSTRACT *This article explores the key technological stages of automotive glass production, their interconnections, and their impact on product quality. The study examines processes such as float glass production, bending, laminating, autoclaving, and final assembly and packaging. Special attention is paid to identifying the main factors influencing defect formation at different stages and methods for their elimination. The importance of float glass quality as the primary material is emphasized. Early-stage defects can propagate through subsequent processes, making initial quality control crucial. The bending process is identified as one of the most complex stages. Factors such as the condition of molding tools, temperature regimes, and the proper grouping of glass in furnace wagons are critical to achieving precise windshield geometry. Temperature monitoring using pyrometers is recommended to ensure accuracy, while improper adjustments to regimes may negatively impact other glass already in the furnace. Laminating and autoclaving are analyzed as essential stages for defining mechanical and aesthetic properties. The interaction between preceding processes and PVB film quality is critical, as misalignment of inner and outer glass layers during manual PVB film application can lead to microvoids and cracks during autoclaving. The final assembly and packaging stage is presented as the ultimate checkpoint for quality control. Comprehensive inspections and robust packaging practices ensure that products meet standards and reach clients in optimal condition. This study highlights the interdependence of all production stages and advocates a systemic approach to quality management. It offers practical recommendations for minimizing defects, optimizing processes, and enhancing efficiency, making it valuable for professionals in the glass manufacturing industry.*

Keywords: *automotive glass; production organization; defect hierarchy; bending process; standardization; glass processing.*

КОМПЛЕКСНИЙ АНАЛІЗ ВИРОБНИЦТВА АВТОМОБІЛЬНОГО СКЛА: ВИКЛИКИ, ДЕФЕКТИ ТА СТРАТЕГІЇ УПРАВЛІННЯ ЯКІСТЮ

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АНОТАЦІЯ *Стаття присвячена дослідженню ключових технологічних етапів виробництва автомобільного скла, їх взаємозв’язку та впливу на кінцеву якість продукції. Розглянуто основні процеси, включаючи виготовлення флоат-скла, молірування, триплексування, автоклавування, а також фінальні етапи комплектації та пакування. Особливу увагу приділено ідентифікації основних факторів, що впливають на утворення дефектів на різних стадіях виробництва, та методам їхнього усунення. На початкових етапах акцент зроблено на критичній ролі якості флоат-скла як основного матеріалу. Етап молірування описано як один із найскладніших у технологічному ланцюгу. Окреслено фактори, що визначають якість геометрії лобового скла, включаючи стан формувального інструменту, параметри температурного режиму та правильність групування скла у вагонетках. Розглянуто методи контролю температури за допомогою пірометрів, а також ризики, пов’язані з некоректним коригуванням режимів у процесі молірування. Особливе місце у статті приділено триплексуванню та автоклавуванню як критичним етапам, що формують механічні та естетичні властивості скла. Висвітлено важливість взаємодії між попередніми процесами та триплексуванням, а також вплив якості ПВБ-плівки на адгезію та візуальні характеристики. Описано ризики, пов’язані зі зміщенням внутрішнього та зовнішнього скла під час укладання плівки, що може призводити до утворення мікропустот і тріщин у процесі автоклавування або подальшої експлуатації. Заключний етап комплектації та пакування описано як фінальний контрольний пункт якості, де здійснюється перевірка продукції на відповідність стандартам та підготовка до транспортування. Наголошено на важливості роботи відділу контролю якості на цьому етапі для запобігання відвантаженню некондиційної продукції. Підкреслено взаємозалежність усіх стадій виробництва та необхідність системного підходу до управління якістю. Запропоновано методи усунення дефектів і оптимізації процесів, що дозволяють* *мінімізувати втрати та покращити продуктивність. Робота може бути корисною для інженерів, технологів і фахівців у галузі виробництва скла, які прагнуть удосконалити свої технологічні процеси.*

Ключові слова: *автомобільне скло; організація виробництва; ієрархія дефектів; процес молірування; стандартизація; обробка скла.*

Introduction

Float glass is a versatile material widely utilized across various industries, including architecture, construction, design, and the automotive sector [1,2]. While each application presents its own complexities, the automotive sector stands out as particularly challenging due to the multitude of influencing factors. These factors arise from the diversity of technological processes and materials employed at different stages of production [3].

Initially, the technological chain for automotive glass production was relatively straightforward, relying primarily on basic annealed or tempered glass [4]. However, since the 1950s, additional processes such as lamination (triplexing), silk screen printing, the application of electrically conductive heating lines using specialized pastes, and other advanced techniques have been incorporated into production workflows [5,6]. Concurrently, the requirements for automotive windshields have become increasingly stringent, focusing on parameters such as safety and weight reduction.

The foundation of this production process is float-glass. The quality of the float glass serves as a critical determinant for the entire production chain, as any primary defect in the glass can evolve into more complex issues during subsequent processing stages [7,8]. Identifying the root cause of defects in the final product is nearly impossible, making it essential to meticulously organize the initial quality control phase and systematically document the data collected during this stage.

While float glass constitutes the primary material in automotive glass production, secondary materials such as polyvinyl butyral (PVB) film, ceramic enamels, and other components also play significant roles. Each of these materials introduces additional complexities into the production process, potentially increasing the likelihood of defects [9].

Moreover, as the number of stages in the technological chain increases, the involvement of human operators at various points in the process multiplies. This heightened reliance on human input significantly raises the impact of human factors, which, in turn, can lead to an increased rate of defects. Additionally, the condition and maintenance of technological equipment represent another critical factor affecting defect rates. Poorly maintained or outdated equipment can exacerbate production issues, and these problems are often indirectly tied to human factors, such as insufficient training of the engineering department. Consequently, the total number of defect variations can reach significant levels. Addressing these issues requires the implementation of training programs and stricter process controls to minimize human error.

One approach to improving product quality is the implementation of methodologies for defect analysis and production management. For instance, the fishbone diagram method (Ishikawa diagram) [10] enables the identification of potential root causes of defects, while the PDCA cycle (Plan-Do-Check-Act) [11] facilitates the step-by-step planning of strategies to minimize these defects.

This study will examine the key technological stages involved in automotive glass production and present practical approaches to addressing the associated challenges.

The goal of the work

The primary objective of this work is to analyze and highlight the key challenges faced in contemporary automotive glass manufacturing. The work aims to provide a basically overview of defect classification systems, illustrating their practical applications, examine technological production chains, and to explore innovative approaches to solving production issues through non-standard and unconventional methodologies.

The main results and their discussion

The automotive glass industry is known for its high labor intensity, primarily due to the numerous processes involved (Fig. 1). In addition to glass, various secondary materials such as PVB film, silk-screen printing glass enamel, heating elements, and plastic parts are used, further adding to the complexity. As a result, the reject rate in this industry is influenced by a multitude of factors across all processes, taking into account the quality of the materials involved. Consequently, it becomes evident that a robust quality control system and well-trained personnel are essential for the smooth operation of enterprises in this field.

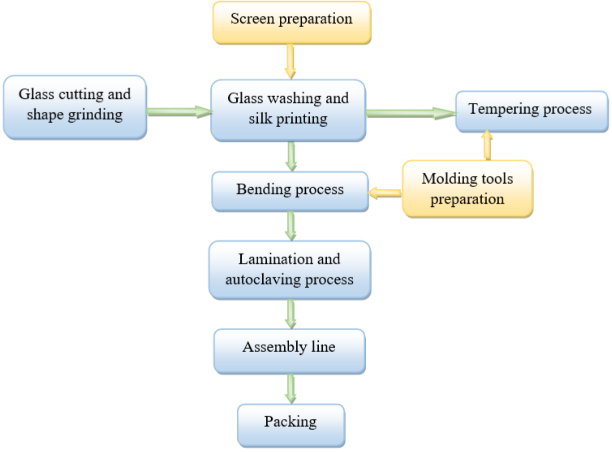

Fig. 1 – General automotive glass production process scheme

First stage of production

Before the cutting process, the first quality control of raw float glass is conducted to identify visible defects such as chips and cracks, as well as to determine the appropriate side of the glass sheet–air or tin [12]. However, beyond these obvious defects, raw float glass may also contain hidden imperfections stemming from storage and transportation conditions, as well as from the specifics of the primary production process. One characteristic defect is the formation of bloom. During the float glass production process, the molten glass passes over a bath of molten tin, and the oxygen concentration in the tin can vary significantly depending on the temperature zones within the bath. For instance, in the medium-temperature zone, local breaches in the seal or other factors can lead to elevated oxygen levels. This results in significant amounts of divalent tin penetrating the glass surface to a shallow depth, creating high concentrations of tin in a thin surface layer. When such glass is heated to 690±10 °C during tempering, divalent tin oxidizes to tetravalent tin. The difference in thermal expansion coefficients between the surface and deeper layers of the glass causes a micro-wrinkled texture to form on the surface. This manifests as a matte white bloom.

When specifying float glass characteristics, it is necessary to consider its draw line orientation, as this impacts subsequent mechanical and optical processing.

These challenges emphasize the importance of comprehensive quality control at every stage of the production process. It is crucial to clearly label glass batches and conduct in-depth investigations whenever defects occur to ensure accurate identification of their root causes and maintain production standards.

Due to the float glass tin-bath process production described above, the resulting sheet exhibits two distinct surfaces: the air side, which does not meet the tin, and the tin side, which directly interacts with the molten metal. Identifying the correct side (Fig. 2) is a critical requirement for subsequent processing stages.

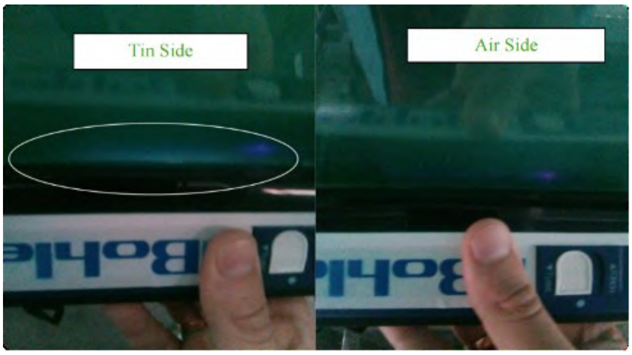

Fig. 2 – Difference between the tin and air sides under ultraviolet illumination

The selection of the side becomes crucial during various stages, such as applying black glass enamel (especially silver paste for heating filaments) during screen printing or laying down PVB film during the lamination process. This attention to detail is essential to maintaining the high quality and functionality of automotive glass in demanding operational environments.

During the glass stages of treatment and grinding, one of the primary causes of defects is the poor quality of abrasive materials. Substandard abrasives can result in edge chipping during thermal treatment, which compromises the structural integrity and appearance of the glass. Furthermore, the quality of abrasives directly affects the uniformity of edge finishing, which is critical for the durability and performance of the final product.

Another crucial aspect that requires attention is the washing process. Specifically, the duration for which the glass remains in a humid environment must be carefully controlled. Prolonged exposure to moisture can lead to partial surface leaching, a phenomenon that becomes particularly apparent during subsequent thermal treatment stages, resulting in visible aesthetic imperfections [13]. Additionally, the use of non-compliant circulating water in washing systems, especially water with high levels of aggressive substances – can exacerbate surface defects. Such water may introduce chemical imbalances that further degrade the quality of the glass surface, necessitating stricter monitoring and treatment of water used in these systems.

Water treatment at the facility level and in washing processes is critically important. Monitoring pH levels, conductivity, and proper chemical treatment is necessary to prevent algae formation and ensure stable equipment operation. For instance, poor washing water quality at the pre-lamination stage (PVB assembly) can halve glass adhesion levels. Similarly, excessive mineral content can rapidly degrade equipment that utilizes facility water, such as grinding systems or autoclave radiator circuits.

The silk screen printing stage

The silk screen printing stage is another critical phase often associated with visual defects (Fig. 3). These defects, while not impacting on the mechanical properties of the glass, significantly diminish its aesthetic appeal and may affect the perceived quality of the product. Manufacturers typically establish their own criteria for acceptable visual distortions, depending on the specific application and customer requirements.

Fig. 3 – Defects in dot silk screen printing

The quality of the printed pattern is heavily influenced by the auxiliary process of screen preparation. Key factors include maintaining proper screen tension, applying the emulsion evenly, and ensuring the technological equipment is in optimal condition. Neglecting any of these parameters can lead to inconsistencies in the printed pattern, such as irregularities in ink distribution, misalignment, or smudging. Moreover, the drying and curing process of the printed enamel plays a vital role in ensuring its adhesion and durability under further processing conditions, such as tempering or lamination.

Functionally, silk screen printing is utilized to create blackout areas, ensuring a clean and uniform appearance by concealing adhesives and structural elements during installation. Additionally, it provides essential shading or UV-blocking properties, enhancing passenger comfort and protecting interior materials from sunlight degradation.

From a technical perspective, silk screen printing facilitates the integration of heating elements, antennas, and sensor interfaces by providing a conductive and durable surface for these components. These functional layers are essential for modern automotive applications, such as defrosting systems and advanced driver-assistance systems (ADAS).

Significant attention must be given to the quality of glass-ceramic enamel, as this factor plays a crucial role in ensuring the overall quality of automotive glass. For instance, the interaction of glass-ceramic enamel with either the air side or the tin side of the glass can result in varying color shades (Fig. 4).

Fig. 4 – Color differences in glass-ceramic enamel after firing due to application on the tin and air sides of the glass

Special emphasis should also be placed on adherence to the specified temperature regimes during the firing process, particularly in the bending (molding) stage of windshield production. Underfiring can result in a low-quality, dark pattern with poor adhesion. Conversely, exceeding the recommended firing temperature outlined in the technical specifications for the glass-ceramic enamel can create excessively high stress within the glass. This not only reduces its technological and functional properties but also negatively impacts the bending process. During the heating of windshield pairs, the upper glass with ceramic enamel may contract along with the contour of the enamel due to its differing viscosity and mechanical parameters compared to the glass. As a result, the geometry between the inner and outer glass is disrupted, rendering the product unsuitable for the autoclaving process (Fig. 5).

Fig. 5 – A crack resulting from the deviation in geometry of the inner glass layer after the autoclave

Additionally, compatibility between the enamel and the type of glass (e.g., clear, green, or dark) must be carefully considered.

Glass tempering

Following the application of the glass-ceramic enamel, the technological chain diverges depending on the type of automotive glass being produced – rear/side glass or windshields. For the first category, the subsequent process involves thermal tempering. At this stage, failure to adhere to tempering protocols can significantly reduce the required strength of the glass and negatively affect its fragmentation behavior during impact testing. In most cases, the root cause of such issues is equipment malfunction, which leads to uneven airflow and, consequently, irregular distribution of internal stresses. This often results in physical failure of the glass.

Bending process

The bending process for windshields is one of the most complex stages in automotive glass production, requiring exceptional attention to detail and the consideration of numerous factors. One aspect is the use of high-quality separators between glass sheets to prevent them from sticking during the process. Proper selection and correct application of these separators are essential for maintaining the integrity of the glass.

For optimal results, molding parameters must be individually tailored to each specific windshield model. This includes grouping windshields based on the complexity of their molding requirements and carefully determining their loading sequence into the furnace wagons. Close attention must be given to the geometry of each glass pair, ensuring that any deviations are identified and addressed in a timely manner through adjustments to the molding regimes. However, these adjustments must be made cautiously to avoid negatively impacting the glass already loaded in the furnace.

Temperature measurements should be conducted using a pyrometer directly on the glass surface to ensure accurate reading. Using thermocouples attached to heating elements as the primary control method is not recommended, as they do not provide a reliable indication of the glass's actual temperature.

An equally important factor is the preparation of molding tools. The quality and condition of these tools play a significant role in ensuring the proper geometry of windshields. Poorly maintained or improperly prepared tools can introduce deviations in glass geometry and may even contribute to physical damage during the furnace process. Regular inspection, cleaning, and maintenance of these tools are essential to prevent such issues and to achieve consistent results.

Additionally, maintaining the equipment in optimal condition is crucial for ensuring consistent quality. Key factors to monitor include the integrity and wear of heating elements, the accuracy of temperature displays, the smooth operation of furnace wagons, the condition of insulation materials, and effective heat dissipation. Any irregularities in these areas can compromise the precision and efficiency of the molding process, leading to defects in the final product.

Laminating and Autoclaving Stages

The laminating and autoclaving stages are critical in ensuring the structural integrity and aesthetic quality of laminated windshields. Notably, nearly half of the defects observed during these stages originate from issues at the preceding molding process (Fig. 6). Thus, seamless interaction and coordination between the molding and laminating stages are central to achieving optimal quality.

Fig. 6. – Result of not correct bending process after autoclaving stage

For proper preliminary vacuuming, it is essential to maintain the glass at the required temperature and vacuum levels for the specified duration in the furnace. Additionally, controlling the microclimate in the production area is crucial, with specific recommendations often provided by PVB film manufacturers. The quality of the PVB film significantly influences the adhesion properties of the final product, as well as the potential occurrence of visual defects. Operator-dependent production factors can be minimized by implementing automated processes, such as automated PVB assembly. The development of fully integrated online manufacturing lines is a key component of mass production capacity for OEM production.

In the production of large-sized windshields, particularly when a non-automated PVB film laying system is used, there is a risk of misalignment between the inner and outer glass layers. This misalignment can create microvoids, which, under the pressure of autoclaving or during subsequent operation, may lead to crack formation (Fig. 7).

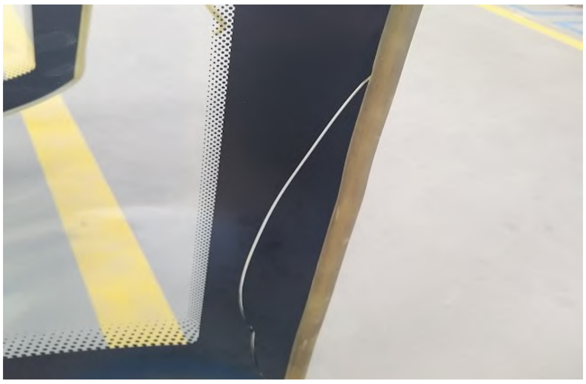

Fig. 7 – A crack resulting from the deviation in geometry of the inner glass layer after the autoclaving process

The autoclaving process itself is highly sensitive to the specified parameters. Deviations from the prescribed regimes can result in weak adhesion of the windshield components or the formation of small, uniformly distributed air bubbles along the edges of the glass. To mitigate these risks, stringent adherence to autoclave protocols is essential.

Moreover, the condition of the equipment used in these stages plays a pivotal role in maintaining quality. Regular inspection and maintenance of heating elements, vacuum pumps, temperature control systems, and other key components are necessary to ensure consistent performance. Any irregularities, such as uneven heating or inadequate pressure, can compromise the integrity of the laminated glass and lead to defects in the final product.

Final Assembly and Packaging Stage

The final assembly and packaging stage represents the concluding phase of the automotive glass production process, during which the manufactured products are prepared for shipment to clients. This stage serves as the ultimate checkpoint for quality assurance, making the role of the quality control department particularly critical. Elevated attention must be given to this phase to prevent the delivery of non-conforming products to customers.

Comprehensive inspection of the finished glass products is performed at this stage to identify any defects that may have been overlooked during previous processes. This includes checking for visible flaws such as chips, cracks, or delamination, as well as verifying adherence to dimensional and geometric specifications. Any detected defects must be promptly documented and addressed to maintain product integrity.

In addition to quality checks, the assembly and packaging team must ensure that the glass is appropriately protected for transportation. This involves using suitable packaging materials and methods to safeguard against mechanical damage, contamination, or environmental factors during transit. The proper labeling of products, including batch information and handling instructions, is also essential for traceability and safe delivery.

By maintaining stringent quality control measures and implementing effective packaging practices, manufacturers can ensure that the final products meet both industry standards and client expectations, ultimately reinforcing their reputation for reliability and excellence. OEM customers typically require 100% transmission optics inspection using Isra or Synerx-type systems, capable of scanning parts within seconds and analyzing specified regions of the glass at a given optical tolerance range (millidiopter). Over recent years, solutions for detecting glass surface defects have evolved significantly and have become a standard in OEM serial production.

Results

The production of automotive glass is an intricate process that demands precision, coordination, and rigorous quality control at every stage. From the selection of raw materials to the final packaging, each phase plays a vital role in determining the overall quality and performance of the product.

Key stages such as molding, triplexing, and autoclaving are particularly sensitive to operational parameters, requiring careful monitoring and adherence to strict protocols. The molding process, for instance, necessitates meticulous attention to geometry, temperature, and equipment condition to prevent defects that can cascade through subsequent stages. Similarly, the triplexing and autoclaving phases rely heavily on the compatibility of materials, precise control of environmental conditions, and the maintenance of equipment to ensure the durability and safety of laminated windshields.

The final assembly and packaging stage acts as the ultimate quality checkpoint, underscoring the importance of effective inspection systems to identify and address any remaining imperfections. Proper handling and protection during this phase ensure that the glass reaches clients in optimal condition, reinforcing the manufacturer's commitment to excellence.

Conclusions

This study highlights the interdependence of all stages in the production chain and the necessity of a holistic approach to quality management. By addressing potential issues at their source and implementing advanced monitoring techniques, manufacturers can minimize defects, enhance efficiency, and maintain a competitive edge in the automotive glass industry. Ultimately, the integration of cutting-edge technologies, continuous staff training, and robust quality assurance systems is essential for meeting the growing demands of modern automotive applications.

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Please cite this article as:

Petrov D., Eronen M., Bragina L., Yashchenko L. Comprehensive analysis of automotive glass production: challenges, defects, and quality management strategies. *Bulletin of the National Technical University "KhPI". Series: New solutions in modern technology*. – Kharkiv: NTU "KhPI", 2025, no. 1(23), pp. 87–93, doi:10.20998/2413-4295.2025.01.12.

Будь ласка, посилайтесь на цю статтю наступним чином:

Петров Д. В., Еронен М., Брагіна Л. Л., Ященко Л. О. Комплексний аналіз виробництва автомобільного скла: виклики, дефекти та стратегії управління якістю. *Вісник Національного технічного університету «ХПІ». Серія: Нові рішення в сучасних технологіях*. – Харків: НТУ «ХПІ». 2025. № 1 (23). С. 87-93. doi:10.20998/2413-4295.2025.01.12.

Надійшла (received) 30.01.2025
Прийнята (accepted) 12.03.2025