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Optimization of the VARTM Process for Prototyping a Bumper Using Hybrid Composite Materials

Optimización del proceso VARTM, para el prototipado de un guardachoque, utilizando materiales compuestos híbridos

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Abstract

To provide an alternative for manufacturing auto parts using composite materials, the Vacuum Assisted Resin Transfer Molding (VARTM) process was utilized to prototype the bumper for the Chevrolet Aveo vehicle. This technique emerges as an alternative for composite material manufacturing, allowing for rapid and high-quality production of advanced composites. In this study, a hybrid composite material reinforced with fiberglass, cabuya fiber, IN2 epoxy resin, an infusion mesh, peel ply, and a vacuum bag was employed. To optimize the VARTM process in bumper prototyping, several simulations of resin flow were conducted with different locations of resin injection and vacuum entry points. Autodesk Moldflow Insight software facilitated the modification and addition of resin injection points to observe the flow evolution, thus determining the filling time for each proposed design. Six different designs were applied for the bumper mold filling. The proposed linear flow design reduced the total filling time of the bumper mold by 81.56% compared to the other five designs analyzed. The result of the numerical simulation was validated through the experimental process, where a high degree of concordance in the mold filling time was achieved between both methods.

Keywords: bumper, cabuya fiber, fiberglass, optimization, resin, simulation, VARTM

Resumen

Con el fin de brindar una alternativa para la manufactura de autopartes utilizando materiales compuestos, se aplicó el proceso VARTM en el prototipado del guardachoque del vehículo Chevrolet Aveo. Esta técnica surge como una alternativa para la fabricación de materiales compuestos, ya que permite realizar una producción rápida y de alta calidad de compuestos avanzados. En el presente estudio, se utilizó un material compuesto híbrido reforzado con fibra de vidrio, cabuya, resina epóxica IN2, una malla de infusión, peel ply y una bolsa de vacío. Para la optimización del proceso VARTM en el prototipado del guardachoque, se llevaron a cabo varias simulaciones de flujo de resina con distintas ubicaciones de los puntos de entrada de resina y de vacío. El software Autodesk Moldflow Insight permitió modificar y agregar puntos de entrada de resina con el fin de observar la evolución del flujo y de esta forma llegar a determinar el tiempo de llenado para cada diseño planteado. Se aplicaron seis diseños diferentes para el llenado del molde del guardachoque. El diseño propuesto de flujo lineal reduce un 81,56 % el tiempo total de llenado del molde del guardachoque en comparación con los otros 5 diseños analizados. El resultado de la simulación numérica fue validado mediante la experimentación del proceso, donde se obtuvo una gran concordancia del tiempo de llenado del molde entre ambos métodos.

Palabras clave: fibra de cabuya, fibra de vidrio, guardachoque, optimización, resina, simulación, VARTM

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1. Introduction

The manufacturing process predominantly employed for producing bumpers is plastic injection molding. This method involves injecting molten plastic under high pressure into a mold, forming the bumper into the desired shape. Despite necessitating costly tooling and substantial capital investment, this process is preferred due to its capacity to consistently produce parts of excellent quality with high reproducibility [1].

As an alternative for manufacturing auto parts, fiber-reinforced composite materials (FRCM) have gained widespread adoption in the automotive industry, particularly for constructing body components. Employing these materials facilitates a reduction in vehicle weight by up to 25%, consequently achieving fuel savings of approximately 5% [2]. One notable technique for fabricating components from FRCM is the Vacuum Assisted Resin Transfer Molding (VARTM). This method utilizes a flexible material known as a vacuum bag to serve as the counter-mold, enabling precise and efficient production processes [3].

In this process, the reinforcing material, typically fibers, is arranged within a mold and encased by a vacuum bag. Vacuum pressure is applied, reducing the internal pressure of the bag, which in turn minimizes air content and enhances the flow of resin through strategically placed pipes within the mold to thoroughly impregnate the fibers. A resin distribution mesh is commonly employed to expedite the resin flow, along with a peel ply that remains unimpregnated by the resin. This methodology enables using cost-effective tools to fabricate high-quality composite parts, thereby establishing it as a favored manufacturing technique across various industries [4]. Figure 1 illustrates the described process.

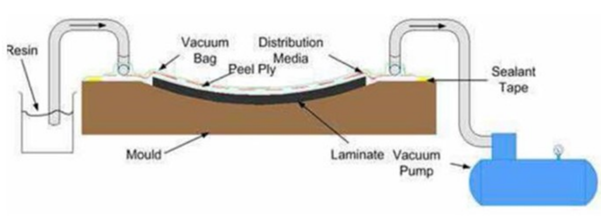

Figure 1. Resin Infusion Process [5]

This process has been widely used for manufacturing different components. Khan et al. [2] manufactured a car body to participate in the Shell Eco-marathon in Malaysia, using the VARTM process. The fibers used for reinforcement were 92110 glass fabric and 260G non-crimp carbon fabric. The epoxy resin LY 5052/Aradur 5052 served as the matrix. In the manufacturing process, a layer of randomly arranged nylon filaments was used to distribute and accelerate resin infusion. Vinyl spiral tubes were used as vacuum and supply conduits. Finally, an Accutrak VPE-1000 device was used to detect leaks. The infusion process began from the innermost central part of the mold and extended to its perimeter, resulting in a car body that weighed14.5 kg, including the metal structure.

The researchers [6] used Resin Transfer Molding (RTM) to manufacture a tire cover, utilizing polyester resin as the base and fiberglass as the reinforcing material with a volume fraction of 14% (equivalent to two layers of fiberglass mats). Mechanical tests conducted on samples of the final product using the RTM process revealeda significant increase of 185% in the elastic modulus and 97% in maximum tensile stress. However, achieving the final product required three unsuccessful attempts to adequately fillthe mold. The issues identified included insufficient resin entry in certain reinforcement areas, attributable to mold design flaws, and elevated viscosities in the resin mixture caused by additives.

In 2016, Pachón and Orozco [7] explored the feasibilityof using release wax as peel ply in the VARTM process to fabricatean air filter cover for a carbureted vehicle. The final product was obtained after six failed attempts, ultimately determining that release wax was unsuitable as a release agent.

As evidenced in previous projects, the VARTM process requiresseveral trial and error tests during the manufacturing stage, demandingexcessive use of resources and time. Additionally, it is essential to ensure that the resin fully impregnates the reinforcing material within the mold when applying the VARTM technique [8]. Air leaks during the infusion process can result in manufactured components havingvoid-rich areas, reducing their mechanical properties [9]. Moreover, the resin infusion process becomes slow for large parts, rendering the method economically unfeasible for large-scale production. According to Reference [10], to perform a proper resin infusion process, the locations of resin entry and air exit points in the mold must be carefully considered.

As evidenced in previous projects, the VARTM process requires several trial and error tests during the manufacturing stage, demanding excessive use of resources and time. Additionally, it is essential to ensure that the resin fully impregnates the reinforcing material within the mold when applying the VARTM technique [8]. Air leaks during the infusion process can result in manufactured components having void-rich areas, reducing their mechanical properties [9]. Moreover, the resin infusion process becomes slow for large parts, rendering the method economically unfeasible for large-scale production. According to Reference [10], to perform a proper resin infusion process, the locations of resin entry and air exit points in the mold must be carefully considered.

To mitigate these issues, numerical simulation of the resin flow front has become an essential tool for optimizing the process. According to Simacek and Advani [11], simulation packages based on RTM molding process models are the only viable option for practical VARTM process simulation and, consequently, its optimization. Below, some studies conducted by various researchers aimed at simulating and optimizing the VARTM process are discussed.

Du et al. [4] determined the optimal positions for resin entry and air extraction points using RTM-Worx software, which simulates the resin flow process. Employing design criteria for placing resin entry and extraction ports in the Vacuum Assisted Resin Transfer Molding (VARTM) process, they found that the entry ports should be located in the central part and along the curves. In contrast, the extraction ports should be positioned at the bumper corners to achieve a shorter filling time.

In 2014, Poorzeinolabedin et al. [10] used PAM-RTM software to conduct several simulations aimed at identifying the most suitable locationsfor resin entry ports and vents in the manufacturing of an exterior part of the Samand Sarir vehicle body. Eight case studies were conducted, each proposingdifferent locations for entry and extraction points to observe the resin flow pattern and filling time. The placement of resin entry points on the right side and extraction points on the left side yielded a simulated filling time of 1203 s, compared to the experimental filling time was 1350 s.

In 2013, Li et al. [12] conducted simulations of the Resin Transfer Molding (RTM) process for manufacturing a wind turbine blade using Moldflow software. These simulations encompassed various parameters, including filling time, temperature, buckling deformation, and pressure evolution, comparing scenarios with and without cooling. The analysis revealed that air bubble formation predominantly occurs at the blade roots and edges. Additionally, it was determined that the filling time is longer when the cooling process is implemented than when it is omitted.

Laurenzi et al. [13] presented the analysis of the numerical process and experimental research for manufacturing a carbon fiber-reinforced beam for an aircraft turbine using resin transfer molding. Initially, they experimentally characterized the permeability value. Subsequently, they conducted process simulations using a modified control volume through the finite element method (FEM-CV). This approach enabled them to explore resin flow front patterns and determine the injection scheme that ensures proper preform impregnation and a filling time compatible with the hardener gelation time.

In Ecuador, bumpers are imported from countries like China, Brazil, and Colombia due to the absence of local companies dedicated to their manufacture. This lack of investment and innovation in manufacturing processes has positioned the country as an importer of this automotive component. Domestic production is confined to manufacturing rear bumpers for pickups and buses, utilizing fiberglass and resins [14].

Academic innovation projects have utilized natural fibers for manufacturing auto parts. One such fiber is cabuya, naturally found throughout the Ecuadorian highlands. This fiber exhibits good mechanical strength (305.15 MPa), high durability, light weight, and other properties that make it suitable for composite materials [15]. Examples of these projects are detailed in [14], where a hybrid composite material (fiberglass + cabuya fiber + fiberglass) was employed to manufacture a bus bumper. The resin deposition was performed manually using brushes and rollers, resulting in favorable mechanical properties. Similarly, Pachacama [16] utilized a composition of 70% resin and 30% cabuya fiber to manufacture a Mazda BT50 pickup hood through Hand-Lay Up and compression molding techniques. This prototype achieved a tensile strength of 85.92 MPa and a maximum flexural stress of 13.72 MPa.

This study introduces an alternative manufacturing process using innovative techniques for producing front bumpers. A prototype front bumper for the Chevrolet Aveo vehicle is fabricated using FRCM with epoxy resin as the matrix, reinforced with mat fiberglass and cabuya fiber, through the VARTM process.

The process simulation was conducted using Autodesk Moldflow Insight software to identify the optimal location of resin entry and exit points within the mold for manufacturing the prototype. For the final production, the assembly of materials and equipment on the prototype mold was carried out considering the information obtained from the simulations to optimize the VARTM process. The following section provides a detailed description of the methodology used to create the bumper prototype.

2. Materials and Methods

2.1. Materials

The properties of IN2 resin with AT30 SLOW hardener used in the fabrication of the bumper prototype are presented in Tables 1 and 2, respectively. These components are manufactured by Easy Composites Ltd.

Table 1. Properties of IN2 Epoxy Resin

Characteristic	Unit	Resin	Hardener	Combined
Appearance	-	Clear liquid	Clear liquid	Clear liquid
Viscosity (25°)	mPa.s	500-800	10-20	200-450
Density	g/cm3	1,08-1,18	1,07-1,13	1,12-1,18

Table 2. Curing Properties of the Hardener

Trade name	Pot Life at 25 °C	Gel Time at 25 °C	Demold Time	Curing Time at 25 °C
AT 30 SLOW	80-100 min	8-11 hours	18-24 hours	24 hours

Fine thread woven cabuya fiber, with a thickness of 0.9 mm, was sourced from a local producer in the province of Loja. For fiberglass, Chopped Strand Mat type distributed by Pinturas América was used. The prototype was fabricated using a combination of Glass + Cabuya + Glass to form the hybrid composite material. Additionally, an infusion mesh and peel ply were employed as optimization tools to fabricate the prototype. Figure 2 illustrates the fibers used in the project.

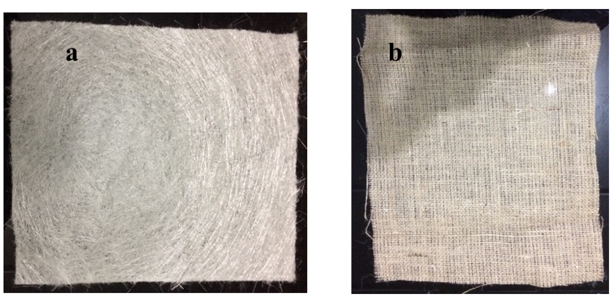

Figure 2. Types of Fibers Used: a) Chopped Strand Mat Fiberglass and b) Woven Cabuya Fiber

2.2. Numerical Simulation

Initially, a numerical simulation of the VARTM process was performed using Autodesk Moldflow Insight software. Six options for resin inlet points and vacuum points were proposed, following the methodology described by [4]. For each configuration, a mold filling time simulation was conducted to identify the option that yielded the shortest filling time.

For the prototype mold filling simulation, determining the permeability of the reinforcement is essential. Given that it comprises a hybrid material (glass + cabuya + glass) and utilizes an infusion mesh with peel ply, its permeability was established following the methods outlined in [17]. Several resin infusion tests were conducted on the hybrid material, with the radial movement of the resin flow front being recorded by filming the process. Figure 3 illustrates the scheme used.

Subsequently, data on the flow front advancement at time intervals of20 s, 40 s, 80 s, 160 s, 320 s, 640 s, and 840 s were extracted from the tests and averaged. Equation (1) was then used to determine the permeability K in both directions K11 and K22. This equation describes Darcy's law applied to radial flows. The porosity data of the fibers were sourced from the literature review, while the volume fraction was set to 40% fiberglass, 20% cabuya, and 40% epoxy resin.

$$K_{ij} = \frac{u\varepsilon}{4t\Delta P}\left\{ {r_f}^2 \left[2.\ln\left(\frac{r_f}{r_0}\right) - 1 \right] + (r_{0^2}) \right\} \quad (1)$$

Where:

- r_f= Radius of the flow front in direction 11 or 22
- r_0= Radius of resin inlet
- mu= Viscosity
- ε= Porosity
- t= Time
- ΔP= Injection pressure

Table 3 indicates the properties of the hybrid material used in the simulation.

Table 3. Permeability Data of the Hybrid Material Used in the Simulation

Material	Volume fraction	Porosity	Permeability (m^2)		
			K11	K22	K33
Chopped Glass, Cabuya	40.2	0.4	3.7327×10^{10}	2.602×10^{10}	3.7327×10^{10}

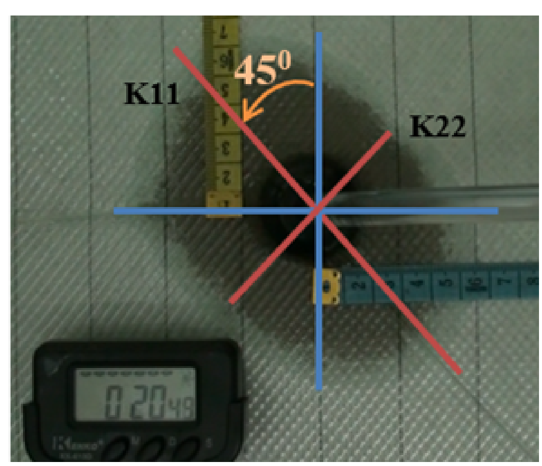

Figure 3. Scheme Used to Determine Permeability

Figures 4, 5, 6, 7 and 8 illustrate the various designs established for placingthe resin and vacuum entry points in the mold filling of the Chevrolet Aveo bumper using VARTM.

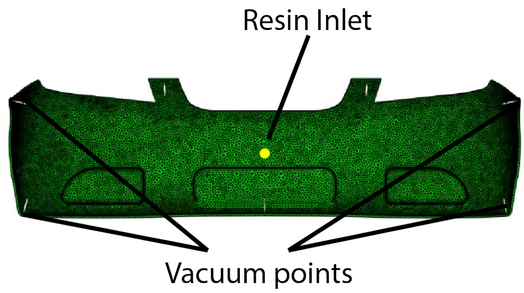

Figure 4. Design 1 (1 Resin Entry Point, 7 Vacuum Points)

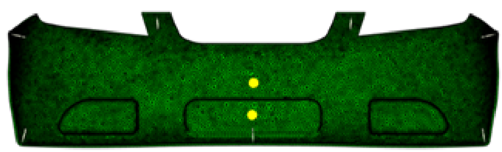

Figure 5. Design 2 (2 Resin Entry Points, 7 Vacuum Points)

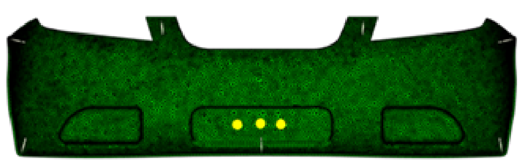

Figure 6. Design 3 (3 Resin Entry Points, 7 Vacuum Points)

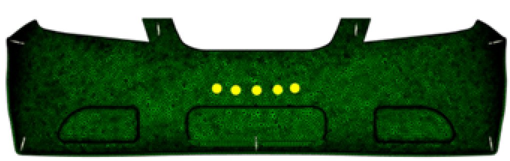

Figure 7. Design 4 (5 Resin Entry Points, 7 Vacuum Points)

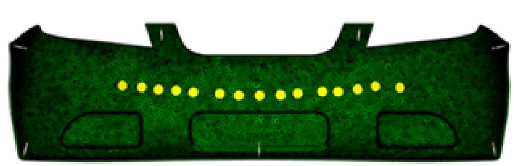

Figure 8. Design 5 (Multiple Resin Entry Points, 7 Vacuum Points)

Figure 9 depicts Design 6, which focuses on optimizing resource utilization and infusion time for the process application. This design strategy proposes multiple resin entry points along the upper edge of the bumper and a single vacuum point at the lower central part of the mold. This design aims to achieve a linear flow from the upper to the lower part of the mold. According to [18], using the linear injection technique results in a shorter filling time compared to the convergent radial injection technique used in permeability characterization.

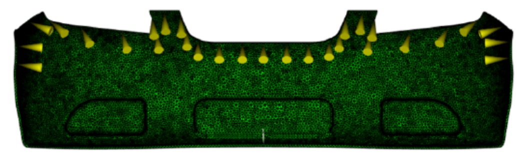

Figure 9. Design 6 (linear flow)

Finally, for each of the proposed designs, a VARTM process simulation is performed to determine which design minimizes the mold filling time. The validation of the selected design is conducted through the experimental process for manufacturing the bumper prototype.

2.3. Manufacturing the Bumper Prototype

First, a mold is constructed from the original bumper by molding its outer part and covering the holes for the headlights and grilles, as depicted in Figure 10. For this process, fiberglass and polyester resin are applied using the Hand Lay-Up method.

Figure 10. Bumper Manufacturing

Next, the mold is prepared by applying a chemical agent compatible with the IN2 epoxy resin to facilitate the demolding of the part. Sealant tape is placed around the mold, as depicted in Figure 11. This ensures that the vacuum bag can be securely sealed to the mold, compacting the fibers when applying vacuum pressure. The fiberglass and cabuya fibers are then positioned on the mold, as illustrated in Figure 12. Given the complexity of the mold, it is advisable to cut small layers of fibers and place them in the corners to ensure complete coverage of the surface.

Figure 11. Placement of Sealant Tape on the Mold

Figure 12. Arrangement of Fiberglass and Cabuya Fibers on the Mold

Peel ply and the distribution mesh are immediately placed over the fibers to accelerate the resin flow. Figure 13 illustratesthe arrangement of these optimization aids.

Figure 13. Peel Ply and distribution mesh over the fibers used as reinforcement.

Next, based on the data derived from the VARTM process simulation, the resin and vacuum entry points are strategically arranged for filling the bumper mold, selecting the configuration from Design 6. A spiral hose is installed to facilitate multiple resin entry points and optimize resources. This hose follows the mold's contour as indicated in the Design 6 simulation, while the vacuum point is situated in the lower central part of the mold. Figure 14 illustrates the placement of the spiral hose and the vacuum point.

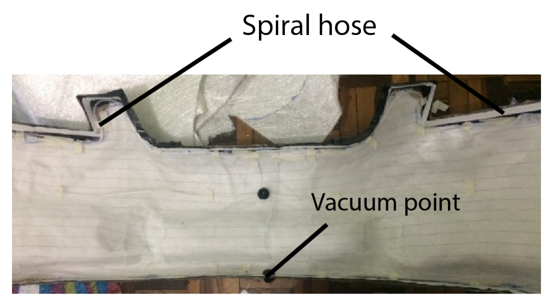

Figure 14. Placement of the spiral hose and vacuum point used for VARTM

After positioning the spiral hose and vacuum point, the vacuum bag is placed over the mold, applying pressure on the sealing tape. This step ensures a complete seal and prevents vacuum leaks. Figure 15 illustrates the placement of the vacuum bag over the mold.

Figure 15. Vacuum bag used for the VARTM process

Next, a vacuum is applied, allowing the resin to flow through the spiral hose to impregnate the fibers in the mold. The conditions under which the VARTM process was conducted for prototype manufacturing are detailed in Table 4. These data were sourced from the Composite Materials Manufacturing Guide by Easy Composites. Finally, the piece is allowed to cure for 24 hours following the infusion, after which demolding is performed to obtain the bumper prototype.

Table 4. Conditions used in the VARTM process

Injection Pressure (Pa)	Temperature (°C)	Resin Viscosity (Pa.s)
88 000	20-25	0.65

3. Results and Discussion

The process simulation was conducted, observing the advancement of the resin flow at various mold filling percentages (25%, 50%, 75%, and 100%). Figure 16 illustrates the progression of the resin flow, indicating that filling 25% of the mold requires 73 s, 50% takes 216 s, 75% is achieved in 432 s, and complete filling (100%) necessitates 865 s.

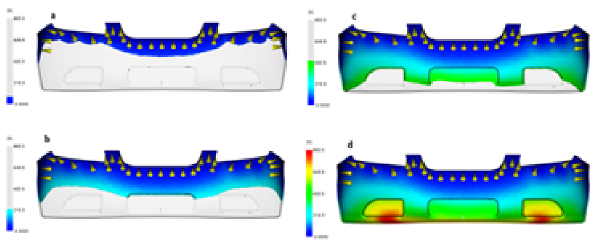

Figure 16. Simulation of the flow front advancement and filling time for design 6 of the VARTM process. a) 25%, b) 50%, c) 75%, d) 100%

The filling times corresponding to each of the previously proposed designs are specified in Table 5. These times were directly derived from the process simulations and serve as a guide for selecting the optimal positions for resin inlet and vacuum extraction points in the production of the bumper prototype.

For the validation of the performed simulation, Figure 17 compares the prototype fabrication using the VARTM process with the proposed Design 6 simulation, which requires the least time. It is observed that the progression of the resin flow front in the experimentation consistently matches the simulated process representation.

After curing the piece for 24 hours, the prototype is demolded. The initially applied chemical agent helps with the demolding of the piece. Figures 18 and 19 show the final piece obtained through the application of the VARTM process for the prototype fabrication.

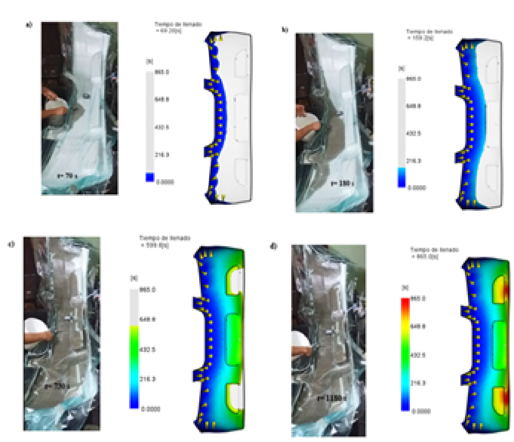

Figure 17. Comparison between the simulation and experimentation of the VARTM process for filling the bumper mold of the Chevrolet Aveo vehicle

Table 5. Filling time for each mold filling simulation design for the bumper

Design	Filling time (s)
1	4691.7
2	3025.4
3	2877
4	2237.7
5	870.7
6	865

Figure 18. Front view of the bumper prototype obtained through VARTM

Figure 19. Side view of the bumper prototype obtained through VARTM

3.1. Discussion

The results obtained from the simulations of the six proposed designs indicate that multiple resin entry points are necessary to improve the efficiency of the filling process. The analysis reveals that in Design 1, which features only one resin entry point located in the central part of the bumper mold, the infusion time is 4691.7 s. As the number of resin entry points increases, as observed in Design 6, which distributes these points along the central axis of the bumper, the infusion time is reduced to 870 s, which represents a decrease of 81.4% compared to the first option. In study [4], which focuses on the flow simulation and optimization of the VARTM process for bumper fabrication, increasing the resin entry points along the central axis of the bumper results in a reduction of 79.8% in infusion time.

To improve the efficiency of the bumper mold filling process, the configuration of Design 6 is proposed, aiming for resource and time optimization. In this configuration, a single vacuum point is incorporated at the lower central part of the mold. In contrast, the resin entry points are positioned on the upper edge of the bumper mold. With this arrangement, the resin travels a shorter distance from the top to the bottom of the bumper mold. The time required to achieve complete mold filling is 865 s, resulting in a unidirectional and uniform resin flow front. Conversely, the optimization study presented by [4] arranged different resin flow fronts, which, upon meeting, can cause the formation of bubbles and dry spots. Additional vacuum points are strategically placed at the intersections of the resin flows to avoid this issue.

In this analysis, using a single vacuum point optimizes the mold filling time during implementation. Choosing to have multiple vacuum points, as in Designs 1-2-3-4-5, would require several vacuum pumps to meet the requirements. Ultimately, Design 6 allows for a notable reduction of 81.56% in infusion time compared to Design 1. It should be noted that although the simulation indicates a bumper mold filling time of 865 s, practical experimentation yielded a time of 1180 s, resulting in a margin of error of 36.41%. Figure 15 illustrates that at the beginning of the infusion, the configuration of the resin flow front in the experimentation differs from that in the simulation, primarily due to the use of the spiral hose. In the simulation, the resin is injected simultaneously through several entry points, while in the experimentation, the injection at the edges is carried out as the resin flows through the internal channel of the spiral hose. This results in a higher resin flow speed at the central point during the experimentation, altering the shape of the resin flow front.

Once the infusion begins, the resin flow front stabilizes, and the numerical simulation data alignwith the experimental results. When the central resin flow front reaches the vacuum point located in the mold, a specific amount of resin that does not impregnate the fibers arranged in the outer edges of the mold is removed. This discrepancy is why the experimentation requires more infusion time than initially calculated in the numerical simulation. This analysis is consistent with the study conducted by [19], which compared the simulation performed in LIMS software with the experimentation of the VARTM process for fabricating an airplane hatch. The time determined in the simulation was 3385 s, whereas it was 5940 s in the experimentation.

In the project presented by [20] for manufacturing a tricycle base using VARTM, some variations were observed between the process simulation and experimentation due to irregularities caused by the deformation of the vacuum bag. Despite these challenges, the cited authors emphasize and recognize the importance of numerical simulations in optimization processes.

During the demolding of the piece, a 15% increase in pressure inside the vacuum bag was noted, preventing the curing process from being conducted under adequate pressure. This pressure increase is attributed to small leaks detected after the infusion process, impacting the bumper's surface quality and generating areas with excess resin. The occurrence of leaks after infusion should be considered in future projects to ensure the production of high-quality parts.

It is worth noting that after the prototype was fabricated, tensile and flexural tests were conducted according to ASTM D3039-08 for tension and ASTM D7264M-07 for flexion on various specimens of the fiber-reinforced hybrid composite material. The results indicate that the material has an average maximum tensile stress of 86.74 MPa and an average maximum flexural stress of 128.73 MPa. When comparing these results with those from projects conducted Paredes [14] and Pachacama [16], it is evident that the tensile and flexural stresses are higher. This improvement is primarily attributed to the technique used for the bumper prototype fabrication, which is vacuum-assisted resin infusion. This method ensures uniform resin distribution and compaction at consistent vacuum pressure, yielding a higher-quality product. In contrast, the projects by [14] and [16] involve manual placement of the resin in the mold, resulting in uneven mold compaction.

4. Conclusions

The bumper prototype for the Chevrolet Aveo vehicle was produced using the VARTM process with hybrid materials. The process optimization was performed using Autodesk Moldflow software and was validated through practical experimentation. Incorporating distribution meshes and peel ply in molding processes with liquid composites is highlighted as a key method for optimization, resulting in a reduction of infusion times by up to 64.4%.

Simulations were conducted for six proposed designs regarding the placement of resin entry and vacuum points using Autodesk Moldflow. The choice of the optimization proposal was based on the filling time results. This proposal featured multiple resin entry points along the upper edge of the mold and a single vacuum point at the base, facilitating the observation of flow front progression. This setup acted as a guide to prevent areas of the fibers from lacking resin impregnation. The proposal emphasized resource optimization by utilizing practical and accessible tools for process experimentation. The simulation tool proved invaluable in minimizing the need for multiple trial and error tests, thereby enhancing the efficiency of producing a high-quality part.

The VARTM process is utilized in various automotive applications and presents several critical aspects. Among these, the imperative to avoid air leaks during resin infusion is paramount to prevent defects in the component and ensure complete impregnation of the fibers used for reinforcement. Additionally, the material and economic resources required for applying VARTM in bumper manufacturing are more accessible than those required for other technologies dedicated to auto parts production.

References

[1] P. Mitschang and K. Hildebrandt, "8 - polymer and composite moulding technologies for automotive applications," in *Advanced Materials in Automotive Engineering*, J. Rowe, Ed. Woodhead Publishing, 2012, pp. 210–229. [Online]. Available: https://doi.org/10.1533/9780857095466.210

[2] L. A. Khan, A. H. Mahmood, B. Hassan, T. Sharif, S. Khushnod, and Z. M. Khan, "Cost-effective manufacturing process for the development of automotive from energy efficient composite materials and sandwich structures," *Polymer Composites*, vol. 35, no. 1, pp. 97–104, 2014. [Online]. Available: https://doi.org/10.1002/pc.22638

[3] J. Summerscales, *Resin Infusion Under Flexible Tooling (RIFT)*. John Wiley & Sons, Ltd, 2012, pp. 1–11. [Online]. Available: https://doi.org/10.1002/9781118097298.weoc216

[4] R. K. Du, F. F. Wang, X. H. Chen, Y. F. Zhang, G. Z. Zhao, and Y. Q. Liu, "Flow simulation and optimization of the car bumper beam by VARTM process," in *Materials Processing and Manufacturing III*, ser. Advanced Materials Research, vol. 753. Trans Tech Publications Ltd, 10 2013, pp. 236–240. [Online]. Available: https://doi.org/10.4028/www.scientific.net/AMR.753-755.236

[5] S. Sunaryo, G. L. Putra, and S. M. Lestari, "Thickness and fiber content optimization in VARTM method for high speed craft," in *Advances in Materials, Processing and Manufacturing*, ser. Advanced Materials Research, vol. 789. Trans Tech Publications Ltd, 11 2013, pp. 412–416. [Online]. Available: https://doi.org/10.4028/www.scientific.net/AMR.789.412

[6] J. G. Anchatuña León and V. H. Loachamín Navarrete, *Construcción de un prototipo de cubreneumático mediante moldeo por transferencia de resina de compuestos*. Tesis Maestría, 2015. [Online]. Available: https://acortar.link/TfrUvy

[7] D. G. Chávez Pachón and E. R. Ledesma Orozco, "Fabricación en fibra de carbón de un accesorio automotriz utilizando el método de transferencia de resina," *Jóvenes en la ciencia*, vol. 2, no. 1, pp. 1838–1842, 2017. [Online]. Available: https://acortar.link/kKHR3L

[8] J. Porto, M. Letzow, E. dos Santos, S. Amico, J. Avila Souza, and L. Isoldi, "Computational modeling of RTM and LRTM processes applied to complex geometries," *Revista de Engenharia Térmica*, vol. 11, pp. 93–99, 10 2018. [Online]. Available: http://dx.doi.org/10.5380/reterm.v11i1-2.62007

[9] C. Wang, G. Yue, G. Bai, L. Pan, and B. Zhang, "Compaction behavior and permeability property tests of preforms in vacuum-assisted resin transfer molding using a combined device," *Measurement*, vol. 90, pp. 357–364, 2016. [Online]. Available: https://doi.org/10.1016/j.measurement.2016.04.058

[10] M. Poorzeinolabedin, L. Parnas, and S. H. Dashatan, "Resin infusion under flexible tooling process and structural design optimization of the complex composite part," *Materials & Design*, vol. 64, pp. 450–455, 2014. [Online]. Available: https://doi.org/10.1016/j.matdes.2014.08.008

[11] P. Simacek and S. G. Advani, "Resin flow modeling in compliant porous media: an efficient approach for liquid composite molding," *International Journal of Material Forming*, vol. 11, no. 4, pp. 503–515, Jul 2018. [Online]. Available: https://doi.org/10.1007/s12289-017-1360-9

[12] C. Li, M. Xu, and Y. Tie, "Simulation analysis of wind turbine blade during resin transfer molding process," *Materials Physics and Mechanics*, vol. 18, pp. 127–134, 01 2013. [Online]. Available: https://acortar.link/Kqm2K2

[13] S. Laurenzi, A. Grilli, M. Pinna, F. De Nicola, G. Cattaneo, and M. Marchetti, "Process simulation for a large composite aeronautic beam by resin transfer molding," *Composites Part B: Engineering*, vol. 57, pp. 47–55, 2014. [Online]. Available: https://doi.org/10.1016/j.compositesb.2013.09.039

[14] M. A. Córdova Suárez and J. G. Paredes Salinas, *Estudio de polímeros híbridos estratificados de matriz poliéster reforzada con fibra de vidrio y cabuya como material alternativo y su incidencia en las propiedades mecánicas en guardachoques para buses*. Tesis de Maestría, Universidad Técnica de Ambato, 2012. [Online]. Available: https://acortar.link/BkoiLh

[15] J. M. Tixe Subina and J. D. Vistín Bastidas, *Aplicación de materiales compuestos para la formación de guardabarros y tapas laterales de una*

moto de 125 cc, 4 tiempos. Tesis de grado, Escuela Superior Politécnica del Chimborazo, 2015. [Online]. Available: https://acortar.link/op1pAM

[16] V. Pachacama, *Diseño, caracterización y aplicación de un material compuesto con base de resina epoxi y refuerzo de fibras orgánicas para la aplicación en un prototipo de capot de la camioneta Mazda BT50*. Tesis de Grado, Universidad de las Fuerzas Armadas, 2015. [Online]. Available: https://acortar.link/bbOfKF

[17] D. B. Peralta-Zurita, D. Jiménez-Pereira, J. V. Molina-Osejos, and G. A. Moreno-Jiménez, "Permeability characterization of a composite reinforced material with fiberglass and cabuya by VARTM process. case hybrid material," in *Recent Advances in Electrical Engineering, Electronics and Energy*, M. Botto Tobar, H. Cruz, and A. Díaz Cadena, Eds. Cham: Springer International Publishing, 2021, pp. 16–30. [Online]. Available: https://doi.org/10.1007/978-3-030-72212-8_2

[18] E. Ruiz and F. Trochu, "19 - flow modeling in composite reinforcements," in *Composite Reinforcements for Optimum Performance*, ser. Woodhead Publishing Series in Composites Science and Engineering, P. Boisse, Ed. Woodhead Publishing, 2011, pp. 588–615. [Online]. Available: https://doi.org/10.1533/9780857093714.4.588

[19] C. L. R. Polowick, *Optimizing vacuum assisted resin transfer moulding (VARTM) processing parameters to improve part quality*. PhD Thesis Carleton University, 2013. [Online]. Available: https://acortar.link/WgvVAV

[20] E. Díaz Escriche, *Simulación y control de los procesos de transferencia de resina en moldes flexibles mediante modelos de permeabilidad equivalente*. PhD Tesis, Universidad Politécnica de Valencia, 2012. [Online]. Available: https://doi.org/10.4995/Thesis/10251/17321