Machine Translated by Google
RCMOS - Multidisciplinary Scientific Journal The Knowledge.
ISSN: 2675-9128. São Paulo-SP.

Year VI, v.1 2025 | Submission: 07/11/2025 | Accepted: 10/11/2025 | Publication: 13/11/2025

Dynamic impregnation control in the filament winding process: impacts on structural efficiency and advanced manufacturing management.

Dynamic impregnation control in the filament winding process: impacts on structural efficiency and advanced manufacturing management

Dynamic impregnation control in the filament winding process: impacts on structural efficiency and advanced manufacturing management

Lucas Emanuel Soeira holds

a PhD in Science (Mechanical Engineering) from the University of São Paulo (USP); a Master's degree in Mechanical Engineering (USP); and a degree in Mechanical Engineering (UNESP).

SUMMARY

This article examines the academic and technical foundations of mechanical process control applied to the manufacture of reinforced polymers. Focusing on the *Filament Winding method,* the study explores the scientific literature on fluid impregnation of fibrous reinforcements and analyzes the limitations of passive wetting systems. The research correlates the homogeneity of the thermoset matrix with the stabilization of the composite's mechanical properties, demonstrating that physical intervention in the fiber architecture reduces porosity defects. It argues that rigorous control of thermodynamic and mechanical variables on the factory floor is the foundation of reliability in sectors with high structural demands.

Keywords: *Filament Winding;* Composite Materials; Fluid Mechanics; Curing Kinetics; ASTM D2290.

ABSTRACT

This article examines the academic and technical foundations of mechanical process control applied to the manufacture of reinforced polymers. Focused on the Filament Winding method, the study examines the scientific literature on the fluid impregnation of fibrous reinforcements and analyzes the limitations of passive wetting systems. The research correlates the homogeneity of the thermoset matrix with the stabilization of the composite's mechanical properties, highlighting how physical intervention in the fiber architecture reduces porosity defects. It is argued that the rigorous control of thermodynamic and mechanical variables on the shop floor is the foundation for reliability in highly demanding structural sectors.

Keywords: Filament Winding; Composite Materials; Fluid Mechanics; Cure Kinetics; ASTM D2290.

1. INTRODUCTION

The pursuit of structural efficiency in contemporary engineering has driven...

continuous development of new forming technologies that align the rigor of

From solid mechanics to the technical imperatives of advanced manufacturing. Within the scope of

Polymer matrix composite materials, the replacement of metal alloys with structures of

High performance has become the standard for industries that demand high...

Strength-to-weight ratio. Energy infrastructure, aerospace transportation, and defense sectors.

critically depend on these anisotropic characteristics. The practical and safe application of these

However, these structures are hampered by the absolute need to guarantee industrial repeatability.

This article is published in open access under the Creative Commons Attribution license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Machine Translated by Google
RCMOS - Multidisciplinary Scientific Journal The Knowledge.
ISSN: 2675-9128. São Paulo-SP.

Year VI, v.1 2025 | Submission: 07/11/2025 | Accepted: 10/11/2025 | Publication: 13/11/2025

Perfect throughout the continuous manufacturing cycle.

The *Filament Winding* process , characterized by the three-dimensional deposition of filaments Tensioned fibers on a rotating mandrel perfectly illustrate the challenge of this optimization. Mechanical. Historically, the impregnation of thermosetting resin inside the filament bundle. *(tow)* was based on cylindrical roller arrangements and passive immersion baths. The literature It points out that these methods are severely limited in ensuring capillary saturation. total, depending almost exclusively on the low initial viscosity of the resin. Air entrapment and the formation of resin - rich areas constitute Chronic microscopic defects that affect the distribution of interfacial stresses in the part. consolidated.

These volumetric discontinuities precipitate delamination under low loads, reducing the The component's lifespan under fatigue conditions is affected, making its certification unfeasible in certain environments. of highly criticality, such as high-pressure offshore pipelines. To overcome this imposed barrier Due to fluid physics, academic research engineering has focused on Development of active interventions in the settling line. The search focuses on mechanisms that act directly on the geometry of the material before it comes into contact with the mold, altering the physical state of the beam to optimize transverse permeability.

The study of the variables involved in the wetting of continuous fibers requires an approach A multidisciplinary approach encompassing thermodynamics, kinematics, and strength of materials. Control The viscosity of the resin and the winding tension determine the degree of consolidation. of orthotropic laminate. This article aims to review the conceptual formulation of dynamic impregnation, detailing the thermal interaction during curing and situating the technologies of Physical alteration of the fiber as a fundamental vector for the enhancement of pressure vessels. industrial.

2. THEORETICAL REVIEW: FLUID BEHAVIOR AND MECHANICS CAPILLARY

The manufacturing process of tubular cylinders using *filament winding* is governed by strict rules. related to the rheology of the resin and the mechanical stress applied to the thousands of filaments Individual pieces of glass, aramid, or carbon. When a cylindrical reinforcement beam crosses a In a wetting bath, the surface tension of the fluid tends to envelop the outer perimeter of the cord. This dynamic creates a film-like barrier that frequently leaves the core of the filaments.

This article is published in open access under the Creative Commons Attribution license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Machine Translated by Google

Year VI, v.1 2025 | Submission: 07/11/2025 | Accepted: 10/11/2025 | Publication: 13/11/2025

The internal parts are completely dry, which negatively affects the final volume fraction of the matrix. Understanding Darcy's law as applied to porous media is essential for diagnosing the resistance to radial flow and to propose interventions that ensure capillarity.

From the perspective of composite micromechanics, the presence of voids (Vv) alters drastically alters the material's stiffness matrix, in which the sum of the fiber volume fractions (Vf), matrix (Vm) and voids must total 1 (Vf + Vm + Vv = 1). The classical theory of laminates It establishes the ability to transfer elastic load between high-strength fibers. It depends entirely on the integrity of the shear provided by the polymer matrix. surrounding area. When the production process fails to minimize Vv , resistance to Interlaminar *shear strength* (ILSS) undergoes decreases that can exceeding 30% invalidates the original design calculations.

Optimizing these parameters illustrates the transition from a production system guided by tolerances. Extensive empirical data for a scientifically driven precision manufacturing process. The implementation of Computerized numerical control (CNC) systems synchronized with tensioning The asset reflects the maturation of process engineering in advanced materials. Innovations in Guidance and impregnation systems emerge as academic and industrial responses to the need to ensure that the manufactured physical object is a replica free of micro-defects in the evaluated mathematical model.

Recent studies demonstrate that the stabilization of the physicochemical properties of the matrix This is reflected throughout the entire component lifecycle assessment chain. Reducing the Internal porosity not only maximizes resistance to thermomechanical fatigue, but also stabilizes dielectric properties and resistance to chemical degradation in environments severe. Such microscopic uniformity constitutes the irreducible foundation for predictability. actuarial data required in regulatory processes aimed at ongoing long-term applications in vital infrastructure.

3. METHODOLOGY OF PHYSICAL INTERVENTION: THE REMODELING OF FIBERS

Technical literature on the physical preprocessing of raw materials points to methods of Geometric alteration of the fiber bundle as the primary mechanical solution for blockages. intrinsic fluids of the resin bath. The mechanical principle of this intervention consists of Applying shape constraints to the path of the tensioned wire. By forcing the transition from one

This article is published in open access under the Creative Commons Attribution license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Machine Translated by Google
RCMOS - Multidisciplinary Scientific Journal The Knowledge.
ISSN: 2675-9128. São Paulo-SP.

Year VI, v.1 2025 | Submission: 07/11/2025 | Accepted: 10/11/2025 | Publication: 13/11/2025

a clustered and cylindrical cross-section into the shape of a flattened and parallel ribbon, a Process engineering multiplies the surface area of contact.

This dimensional expansion maximizes the fiber's exposure to the resin immediately before... consolidation stage on the mandrel, breaking the surface tension that isolated the core from the beam. The thermodynamic and fluidic result of this methodological application is saturation. Accelerated by optimized capillary action, which eliminates the formation of *dry spots* .

To ensure the complete wettability of each isolated filament, interfacial adhesion is guaranteed. Chemistry occurs in its theoretical fullness.

The application of mechanical methods of this nature directly impacts the statistics of reliability of large-scale production. In practical terms of structural evaluation, the Suppression of elementary defects is reflected in the reduction of the standard deviation in the tests. Mechanical factors, reducing the dispersion of ultimate resistance data. The predictability of the limit. The failure rate in laboratory tests increases exponentially, aligning with the sample response. physics applied to the rigorous fracture mechanics models previously drawn up in the environment computational.

In addition to structural gains, the systematization of control mechanisms for the architecture of Fiber enables a much more stable operation in the face of climatic fluctuations in the environment. manufacturing. By reducing the exclusive dependence on factors such as ambient temperature and Due to the temporary viscosity of the resin, the deposition system becomes more robust. It then becomes... To withstand slight variations in the properties of the polymer batch without sacrificing integrity. Impregnation of the manufactured tube, protecting the production line against high rejection rates. and refuse.

4. Thermodynamic variables and matrix curing kinetics POLYMERIC

The structural stability of a part manufactured using Filament Winding is not limited to geometric stage of deposition; it is inseparable from the thermal crosslinking phase of the matrix. Thermosetting. The epoxy or polyester resin, when subjected to the curing process, undergoes a reaction. violent exothermic reaction. During the oven heating cycle, the viscosity of the resin... It drops exponentially before reaching the gel point . One Irregular impregnation generates catastrophic thermal gradients inside the wall of the composite, in which the resin-rich zones accumulate heat, while the dry areas act

This article is published in open access under the Creative Commons Attribution license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Machine Translated by Google
RCMOS – Multidisciplinary Scientific Journal The Knowledge.
ISSN: 2675-9128. São Paulo-SP.

Year VI, v.1 2025 | Submission: 07/11/2025 | Accepted: 10/11/2025 | Publication: 13/11/2025

as undesirable thermal insulators.

The homogeneity of the volume fraction (Vf), guaranteed by pre-processing and by Mechanical remodeling of the fiber bundle acts as a global thermodynamic stabilizer. of the structure. The fiberglass or carbon fiber conducts the heat generated by the exothermic reaction of uniform form throughout the laminate. When impregnation is perfect, no peaks occur. isolated temperatures (hot spots) that would lead to localized thermal degradation of polymer or the emergence of acute residual stresses during post-cure cooling.

Control over the degree of resin conversion (curing kinetics) dictates the final properties of Glass transition temperature (Tg) of the structural composite. Thick parts, characteristic of vessels. Pressure vessels designed for the storage of hydrogen or natural gas are particularly sensitive to this phenomenon. If thermal curing occurs asymmetrically due to poor Due to the matrix distribution, the cylinder will develop warping and interfacial microcracks before even after being removed from the chuck and subjected to its first hydrostatic working load.

Therefore, refining the mechanical wetting step has a profound and preventative impact. in the thermodynamics of the part. By ensuring that each fiber is perfectly enveloped by a micrometric and constant polymer layer, the process engineer ensures that the The transient heat transfer equations applied in the design act symmetrically in throughout the thickness of the cylindrical shell. This eliminates the generation of shock-induced defects. Internal thermal insulation consolidates the physical integrity of the equipment.

5. Regulatory Impacts and Standardized Assessment Tests

For composite manufacturing to be incorporated into high-risk infrastructure projects, operated by state or multinational bodies, innovations in impregnation control They must be validated in accordance with a rigorous regulatory framework. The impact of A uniform distribution of resin is empirically proven through the application of standards of the *American Society for Testing and Materials* (ASTM). The ASTM D2290 test *(Apparent Tensile Strength of Ring or Tubular Plastics by Split Disk Method),* popularly Known as the *NOL Ring test,* it is the standard metric for measuring circumferential strength. continuous of the rolled piece.

Test specimens extracted from pipes with a high porosity index, due to poor impregnation, they fail prematurely in the split disk test (NOL Ring), exhibiting interlaminar shear faults occur long before the maximum tensile strength of the fibers is reached.

This article is published in open access under the Creative Commons Attribution license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Machine Translated by Google

Year VI, v.1 2025 | Submission: 07/11/2025 | Accepted: 10/11/2025 | Publication: 13/11/2025

achieved. The application of beam scattering and reshaping devices raises

The values of tensile strength in this test were approximately the values at which the rupture stress was measured, as attested in the laboratory report.

The effectiveness of the advanced manufacturing technique and validating the component before auditors.

technicians.

Simultaneously, the chemical qualification of the production batch depends on methodologies such as

ASTM D2584 *(Ignition Loss of Cured Reinforced Resins),* which determines the volume fraction.

The exact fiber (Vf) is obtained by calcining the polymer matrix in a muffle furnace at high temperature. A process

Well-managed filament *winding* exhibits not only a high percentage of fiber

(often exceeding 65% in volume), but, mainly, an insignificant variance.

this percentage among different samples taken from the same tube, proving the

stability of the resin bath and tensioning.

Translating this conformity into advanced manufacturing management involves achieving

Quality certification without reservations. When the reports attest to the absence of voids (Vv <

(2%) and the very high apparent tensile strength, the manufacturing company is eligible to compete for

Rigorous bidding processes in the naval defense and deep-water oil extraction sectors.

Submission to standardized tests ceases to be a bottleneck for rejection and becomes

in an irrefutable mechanism for proving the technological mastery of engineering over

the subject matter.

CONCLUSION

A thorough review of the mechanical and thermodynamic mechanisms involved in

The impregnation of composite materials establishes that the strict regulation of architecture

The primary fiber is the key factor in increasing elastic safety. By reconfiguring the bundle

Through reinforcement via geometric constraints, precision mechanics offers a response.

definitive for the eradication of chronic discontinuities and thermal stabilization during the

resin curing, systematically raising the quality matrix of cylinders subjected to high temperatures.

pressures.

In the spectrum of computer-aided structural design, the physical guarantee of a fraction

Volumetric analysis, free from porosity gradients, transforms analytical practice. Engineers

Engineers gain a solid foundation for reducing excessively high safety coefficients.

conservatives in the design phase, based on the certainty that the modeled anisotropy will not be

compromised by hidden defects on the factory floor. This synergy between controlled manufacturing

This article is published in open access under the Creative Commons Attribution license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Machine Translated by Google

Year VI, v.1 2025 | Submission: 07/11/2025 | Accepted: 10/11/2025 | Publication: 13/11/2025

Simulation enables the design of substantially lighter, more economical infrastructures.
and efficient.

Furthermore, fluid and mechanical optimization corroborates the essential guidelines of manufacturing.
Sustainable in the 21st century. The strictly necessary absorption of resin volume, imposed
Due to its well-structured capillary system, it prevents chronic dripping and mass disposal of
surplus thermosetting polymers. Mitigating the unnecessary use of resins derived from
Petroleum aligns the Filament Winding process with macroeconomic and environmental objectives.
global initiatives to reduce toxic industrial liabilities.

In summary, the conceptual and applied advancement in wetting techniques consolidates a pillar of...
Tangible innovation. Interdisciplinary scientific deepening — encompassing Darcy's law.
for fluids, the thermal kinetics of polymer reactions and the normative requirements of ASTM.
— This attests to the maturity of the structural composites sector. Understanding and intervening in the trajectory of
Fluid at the micrometer scale has proven to be the non-negotiable path to ensuring stability and
macroscopic safety in components that underpin critical global operations.

REFERENCES

MALLICK, PK **Fiber-Reinforced Composites: Materials, Manufacturing, and Design.** 3rd ed. Boca Raton: CRC Press, 2007.

PETERS, ST **Composite Filament Winding.** Materials Park: ASM International, 2011.

ASTM D2290-19. **Standard Test Method for Apparent Tensile Strength of Ring or Tubular Plastics and Reinforced Plastics by Split Disk Method.** ASTM International, West Conshohocken, PA, 2019.

ASTM D2584-18. **Standard Test Method for Ignition Loss of Cured Reinforced Resins.** ASTM International, West Conshohocken, PA, 2018.

This article is published in open access under the Creative Commons Attribution license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.