

# VARTM Processed Composite Materials

Subjects: Polymer Science

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Fiber-reinforced composite structures are used in different applications due to their excellent strength to weight ratio. Due to cost and tool handling issues in conventional manufacturing processes, like resin transfer molding (RTM) and autoclave, vacuum-assisted resin transfer molding (VARTM) is the best choice among industries. VARTM is highly productive and cheap. However, the VARTM process produces complex, lightweight, and bulky structures, suitable for mass and cost-effective production, but the presence of voids and fiber misalignment in the final processed composite influences its strength. Voids are the primary defects, and they cannot be eliminated completely, so a design without considering void defects will entail unreliability. Many conventional failure theories were used for composite design but did not consider the effect of voids defects, thus creating misleading failure characteristics.

Keywords: vacuum-assisted resin transfer molding (VARTM) ; void defects ; composite materials ; material processing

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## 1. Introduction

Composite materials have significant properties like their high strength to weight ratio <sup>[1][2][3]</sup>. They are used in many industries for different complex structures, such as aircraft, automobiles, marine, and sports. Polymer matrix composites (CFRP and GFRP) are widely used composite materials <sup>[4][5][6]</sup>. Different manufacturing processes are used to fabricate composite parts like hand layup, autoclave, out-of-autoclave (OoA), and additive manufacturing (AM) <sup>[7][8][9]</sup>. The autoclave is a highly labor-dependent, time-consuming, and costly process not suitable for mass production. Additive manufacturing is also a well-known fabrication technique based on adding material. Now, this process is also improved at a significant level for better quality. However, for large and bulky products, this will be costly, time-consuming, and can affect shape quality. Postprocessing is another issue in this process <sup>[10][11]</sup>. Out-of-autoclave processes are less costly and based on oven/mold <sup>[12][13]</sup>. Liquid composite molding (LCM) is an appropriate OoA technique that can produce complex shapes with high quality and quantity. Resin transfer molding (RTM) specifically is mostly accepted among industries, having numerous advantages to manufacture complex aero-engines and automotive parts <sup>[14]</sup>. The matched metal tooling process in the RTM is costly, and for manufacturing large and bulky structures such as boat hulls, tool design is complicated. Vacuum-assisted resin transfer molding (VARTM) was developed to modify the traditional RTM process to diminish the cost and design difficulties linked with bulky metal tools. Due to the cheap and mass-productive advantage of the VARTM process, it is developing day by day.

Initially, the VARTM cycle's advancement was introduced by Williams, Summerscales, and Gove in their noteworthy review of resin injection under flexible tooling (RIFT) <sup>[15]</sup>. In 1950, The VARTM process was presented, and furthermore, vacuum infusion process (VIP) or resin infusion under flexible tooling (RIFT) were investigated. Later, different groups worked for a variant of VARTM like Lotus Car Ltd. Then, in 1980 and 1985, Gotch extended and replaced one half of the mold with a silicone vacuum rubber bag, incorporating vacuum pressure to draw the resin from a resin supply into the dry preform <sup>[16]</sup>. In 1990, Seemann patented the Seemann composite resin infusion molding process (SCRIMP) as a variant of the VARTM process, which is widely used for manufacturing large composite structures <sup>[17]</sup>. Fast remotely actuated channeling (FASTRAC) is another developed variant of the VARTM process to reduce waste <sup>[18]</sup>. Some other studies were also recommended to spread external compaction pressure. such as the inflatable bladder, permanent magnets, or pressurized air to reduce process-induced voids and increase fiber volume fraction <sup>[19][20][21]</sup>. Despite that, due to the restriction of estimating clamping powers, these recommended variations of VARTM are limited to small and medium-size composite parts. Other variants, such as double bag vacuum infusion (DBVI), vacuum-assisted process (VAP), and controlled atmospheric pressure resin infusion (CAPRI), were also developed and patented to enhance repeatability of the process and to minimize void contents and the intrinsic thickness gradient <sup>[22][23][24]</sup>.

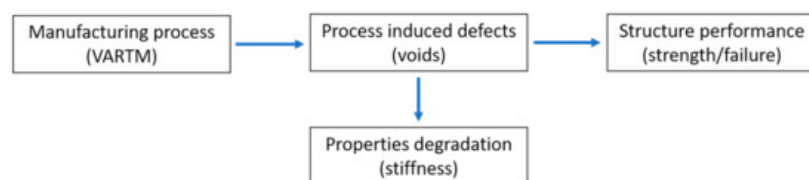
However, because of the mass and cost-effective production environment, the VARTM manufactured products contain voids and micro-voids as ordinary deformities which influence the composites' applications <sup>[25][26][27]</sup>. The production of voids and flaw-free composites will be costly and not feasible, so it is necessary to consider the effects of voids defects

and their progression, even in the design cycle's beginning phases. Different experimental or analytical studies have proven that these defects are responsible for initiating and evolving damage actions and then certainly affect the critical state of final failure [28][29].

It is an important topic to determine failure state and components' effectiveness due to growth in the advanced application of composite structural materials in current years. When the final processed composites present flaws, then it is necessary to incorporate manufacturing defects in failure theories. There are many failure criteria for composites which have been developed without consideration of voids. These are summarized in [Section 3](#). Researchers have started to work and estimate the strength of composites with manufacturing defects. Many studies have shown that voids diminish the transverse tensile and compressive strength of laminate at the application level and decrease the trustworthiness of manufactured composites. Composite defects should be taken into consideration because they influence many functionalities of composite products. Air voids are the most common influenceable flaws, significantly affecting the application and eligibility of composite structures [30]. Experimental studies showed that voids and microcracks are the common known defects in textile composite materials caused by the manufacturing process [31].

Void-free manufacturing is impossible, but to work safely at the application level, reliable design is necessary [25][27][32]. That's why today's performances under defects are studied, and different approaches are coming into the picture to make it feasible [33]. The suitable failure theory could be incorporated into the performance evaluation process when the defect information is gained from previous material characterization and manufacturing processes.

[Figure 1](#) shows the manufacturing process and its defect and effects of defect on manufactured components. This review presents the VARTM process (polymer matrix composites) as cost-effective, failure theories with and without considering voids, the need to consider voids, and suggested failure theories to consider defects (voids). Some suitable failure theories have been discussed comprehensively, which are capable for composites in voids scenario and save the design from misleading. Every suggested criterion has its advantage for a designed application. A strain-based criterion was suggested for a primary or initial check of failure. Discrete damage mechanics is suitable as it considers voids as a crack or void density and its evolution function. Fracture mechanics (virtual crack closure technique (VCCT)) was suggested for delamination, which is the case of void growth, and a micro-mechanics study was discussed for the estimation of failure at the micro level due to voids and their effect on macro-failure. These theories were suggested to consider the effect of voids in composite failure design, and these are also well established in the finite element method (FEM) to save time and costs for predesign. Based on this review for failure theories, one can obtain the importance of manufacturing conditions in the design strategy, and in the future, further enhanced and accurate criteria can be established considering manufacturing effects like voids among others.



**Figure 1.** Process and effect of defects (voids).

## **2. VARTM Process**

The vacuum-assisted resin transfer molding (VARTM) process has been developed to use effectively during the past two decades. This closed-mold technique can produce high performance and various types of composites, especially fiber reinforced polymer structures, at low cost [34]. The method involves primarily putting the fibers or cloth fabrics in a preform in the desired configuration. Often, these fabrics are held together by a binder and pre-pressed to the mold shape. A top (second) matching mold tool is clamped over the first and vacuum-sealed used as a deformable vacuum bag. Then, the pressurized resin is injected into the cavity by the aid of vacuum [35].

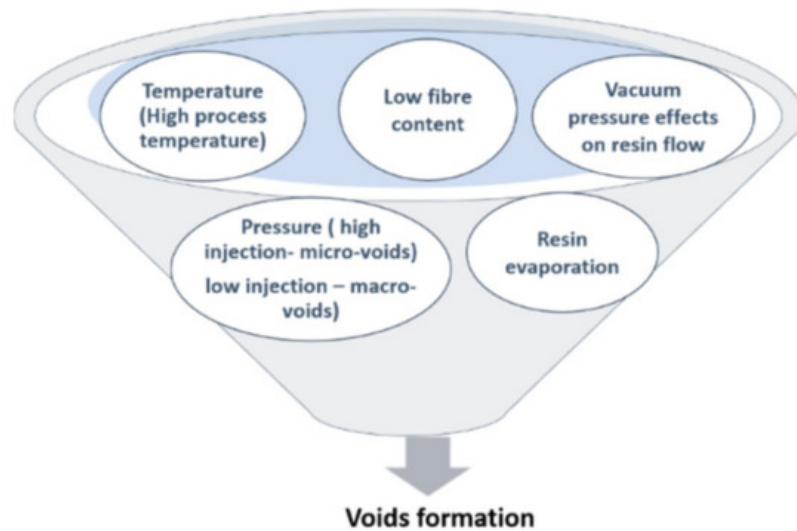
Afterward, the laminate is healed, and both injection and cure can occur at either ambient or elevated temperature. In this process, it is possible to use any fibers, and the stitched materials work well since the gaps allow for the rapid transport of resin [36]. This is a flawless process using low-cost composite materials without prepregs and autoclaves compared with the conventional composite fabrication process used in the aeronautical field. The resin cup is typically open to the atmosphere, creating a pressure differential between the inlet and exit, causing the resin to be drawn into the layup [37]. [Figure 2](#) shows a typical VARTM process setup.

The main benefit of VARTM is that it lies in the low injection pressures (approx. 1 atm). At the time of manufacturing, less movement is required for reinforcement, which has been achieved by this little pressure to get better quality products [40]. Due to the advantage and improved understanding of process physics, VARTM is employed in various railroads, naval, aerospace, and automobile parts with many variations of VARTM, and more complex composite parts with higher quality.

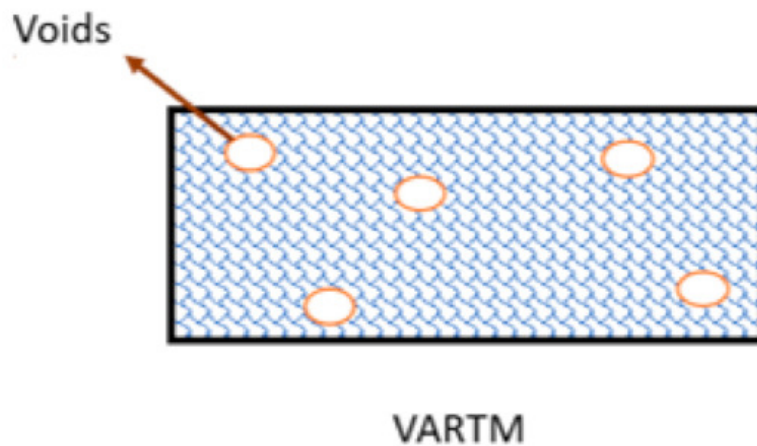
strength, and lower cost can be produced [34][38]. Although there are advantages of VARTM process and it is used widely, for accurate design, its primary defects' (voids) effect should be known and considered alongside the formation of voids, as summarized below.

## 2.2. Defects in VARTM Processed Composites

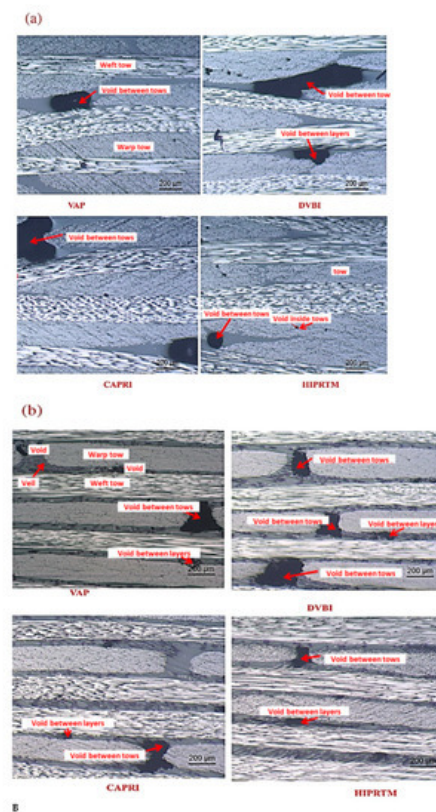
Over the VARTM process's advantages, there are different types of defects, like fiber misalignment and voids, whereby defect-free manufacturing is impossible. In mass production, voids formation is the primary defect. Many factors like resin-flow pressure variation or temperature changes initiate voids formation in this process [41][42]. Figure 4 shows void formation factors in the VARTM manufacturing process. In the VARTM process, void content is a significant issue in mass production and a cost-effective environment [26]. It reduces strength and the modulus which creates an early failure of composites in a loading environment [25][27]. This is why taking care of voids in failure theories remains very important to safe instead of misleading design. Figure 5A shows the voids scenario's schematic in the VARTM processes to demonstrate a high void content in the process. Figure 5B illustrates actual images of voids in different VARTM processes for woven (a) and non-crimp (b) reinforcement from experiments [14]. This figure indicates that the voids' conditions are higher in the mass production process (VARTM). This is why it is necessary to consider the manufacturing details (voids effect) in failure design conditions.



**Figure 4.** Voids formation factors.



A



**Figure 5.** (A) Voids demonstration (Schematic), (B) (a) Voids in different VARTM processes for woven reinforcement, (b) voids in different VARTM for non-crimp reinforcement adapted from [14], with permission from Elsevier, 2021.

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