Out-of-Autoclave Process for Composite Manufacturing

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Composite materials have gained increased usage due to their unique characteristic of a high-stiffness-to-weight ratio. High-performing composite materials are produced in the autoclave by applying elevated pressure and temperature. The process is characterized by numerous disadvantages, such as long cycle time, massive investment, costly tooling, and excessive energy consumption. As a result, composite manufacturers seek a cheap alternative to reduce cost and increase productivity. The out-of-autoclave (OoA) process manufactures composites by applying vacuum, pressure, and heat outside of the autoclave.

Keywords: autoclave ; out-of-autoclave ; resin transfer molding

1. Introduction

The composite material is formed by combining a fiber reinforcement and a binding matrix [1]. The resulting material is lightweight but has high strength and stiffness [2]. Composite materials offer exceptional properties such as high thermal stability, flexural strength, damping property, corrosion resistance, impact resistance, and fire resistance [3]. Due to their exceptional properties, composite materials are useful in various industries such as aerospace [4], space exploration [5], construction [6], automobile [7], biomedical [8][9], sports [10], and marine [11]. Based on fiber types, composites are categorized as particle reinforced composites, discontinuous fiber-reinforced composites, and continuous fiber-reinforced composites. Composites made of fibrous reinforcements are stronger and stiffer than those made from particulates and are referred to as fiber-reinforced plastic (FRP). In FRP systems, the fiber acts as the load-carrying member, and the matrix binds the fibers together, protects the fibers from abrasion and the environment, and acts as a load transfer medium. Fibers commonly used in FRP systems are glass, carbon, aramid/Kevlar, and boron fibers. These fibers are combined with the polymer matrix in either a chopped or a continuous form. Based on the matrix used, composites are categorized into polymer matrix composites (PMC), metal matrix composites (MMC), ceramic matrix composites (CMC) [12], or hybrid composite materials [13]. PMC-wide usage can be attributed to its flexibility in fabricating complex and large shapes. Thermosetting or thermoplastic polymers are used as matrix components. Thermoplastic polymers can be subjected to repeated heating and cooling cycles. In contrast, a thermosetting polymer cannot be reversed after curing [14]. Commonly used thermoplastic polymers are polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), and examples of thermosetting polymers are epoxy, unsaturated polyester, polyimides, and bismaleimides [15]. Thermosetting polymers are often used to fabricate polymer-based composites because of their ease of processing.

Autoclave processing is typically used for fabricating fiber-reinforced plastic (FRP) composites for high structural applications [16]. Layers of fibers pre-impregnated with resin (known as prepreg) are stacked on a mold to form the desired component shape. The assembly is covered with different layers of bleeder and breather and then sealed with a vacuum bag. The bleeder helps absorb excess resin squeezed out from the laminate, and the breather creates a channel through which air and volatiles are ejected from the assembly [16]. The mold-laminate assembly is placed in the autoclave, a large, temperature, and pressure-controlled vessel. The bag is connected to the vacuum system, and a predetermined temperature and pressure (cure cycle) is applied to the laminate. The temperature initiates and sustains the chemical reaction to cure the resin. The pressure compacts the laminate to the desired fiber volume fraction and collapses any void present during curing. In addition, the pressure conforms the laminate to the tool surface. Several models have been developed to simulate autoclave curing for efficient processing [17]. For example, the cooling and reheating cure models were developed to prevent a thermal spike from an exotherm reaction, leading to partial degradation when curing a thick composite [18]. Furthermore, incorporating the smart cure monitoring model [19] has helped optimize the cure cycle in autoclave curing. An optimized autoclave curing is believed to reduce the cost of processing. Though the product of the autoclave process is a high-performance and reliable composite structure, many manufacturers are concerned with its numerous drawbacks. Some of its disadvantages are massive investments, excessive energy consumption, and costly tooling. Consequently, only the aerospace industries can conveniently afford the costs due to safety reasons. Most manufacturers are turning to other alternatives.

The out-of-autoclave (OoA) process manufactures composites by applying a vacuum, pressure, and heat outside the autoclave [20]. The OoA process uses lower pressure than the autoclave and cures composites in an oven or heat blankets. Hence, a special resin system is developed to evacuate voids efficiently [21]. Though the OoA process is more cost-effective than autoclave curing, the quality of composites manufactured by this process is still inferior to those processed in the autoclave [21].

2. Prepreg

Prepregs are sheets of unidirectional fibers pre-impregnated with a partially (B-stage) cured resin matrix [22]. Prepregs are produced by placing fibers between two resin sheets, usually epoxies, and passing the fibers through rollers to achieve complete wet-out. In order to prevent premature curing, the wetted prepreg is wound up and stored in a refrigerator (typically at −18 °C) [22]. Prepregs are available in varieties of widths ranging from 3 inches to 72 inches, depending on the dimension of the machine used. Their thickness ranges from 0.01 mm to 0.8 mm, depending on the type of fiber form used. Common fiber prepregs include unidirectional tapes and woven and prepreg tows [23]. Different types of resin used for prepreg manufacturing are epoxies, phenolics, and cyanate esters [24]. Prepregs are very flexible, which permits them to be shaped to fit a complex mold. Furthermore, prepregs have sticky surfaces due to the partially cured resin, which facilitates the prepreg layers' stacking and prevents possible movement. Prepregs can be laid either by the manual lay-up process or by automation [25].

3. Vacuum Bagging

The vacuum bagging process uses a flexible transparent film to enclose and compact wet laminates using atmospheric pressure [26].

This method uses a vacuum pump to extract the air inside the vacuum bag and then compresses the part under atmospheric pressure [27]. The resin is squeezed and sucked from the wet laminate into the bleeder (woven polyester fabric). Materials used in the vacuum bagging process are cheap, yet the parts fabricated with this process yield better mechanical properties than hand lay-up. Furthermore, the applied pressure is evenly distributed over the entire surface regardless of the quantity and type of material processed. The effect of evenly applied pressure is a thinner laminate with fewer voids [28]. Therefore, the process effectively controls excess resin in the laminate that increases the fiber volume fraction. Furthermore, it is a simple process that can use a variety of molds. However, some of the disadvantages of using this process are that with a bigger and more complex lay-up comes more support which increases labor. The process needs to be completed once started without having a break in between. Fiber volume fraction cannot be effectively calculated as other methods, mainly when over-bleeding occurs. The vacuum bag technique can be used to fabricate yachts, primary structures such as decks, hulls, superstructures, bulkheads, and secondary structures such as partition panels and interior joint work [29]. The vacuum bagging process has shown considerable improvements in the mechanical properties of fabricated parts compared to hand lay-up processing. However, hand lay-up parts are inferior to parts manufactured by the vacuum infusion process.

4. Vacuum Bag Only (VBO)/Oven Cure

Vacuum bag only (VBO) curing is an out-of-autoclave (OoA) technique for processing composite laminates. It is performed in a contemporary oven without external pressure, such as the autoclave, to consolidate the laminate. In the absence of elevated pressure, it is important to consider the OoA resin property, fiber bed architecture, and prepreg system. The OoA resin is a slow cure kinetics and low cure temperature matrix system. The manufacturing assembly of a vacuum bag only composite, with its consumables is presented. The OoA prepregs are characterized by a partially impregnated microstructure that presents in-plane permeability, which permits air evacuation and aids the manufacturing of low-porosity parts without using autoclave pressure [30]. The partially impregnated microstructure includes dry spots and resin-rich regions. Low pressure of 0.1 MPa is available for consolidation during cure, and it is insufficient to prevent void formation [31]. Therefore, the entrapped air, moisture, and other volatiles in the laminate must be evacuated before the resin gels. As a result, the dry regions in the partially impregnated microstructure form an internal network that facilitates gas exit during the initial low-temperature stage of cure. At high temperatures, the dry areas are infiltrated by resin from the resin-rich region. Repecka and Boyd [32] reported that partially impregnated prepregs resulted in a void-free panel, while fully impregnated prepregs led to over 5% void content. An impregnation level of 60% has been found to produce void-free panels. However, Ridgard [33] highlighted that the degree of impregnation should be considered regarding resin viscosity, cure cycles, and laminate quality. Yang and Young [34] demonstrated that the degree of saturation of a VBO prepreg affects the mechanical properties of laminates. The laminates were made with epoxy resin. Fully impregnated carbon fiber and dry fibers were assembled as hybrid laminates, and different degrees of saturation were defined; over-saturation, saturation, and undersaturation. Laminates with over-saturation exhibited similar mechanical properties as those fabricated with the autoclave. For over-saturation to occur during VBO processing, conditions should favor the impregnation rate. Centea et al. [35] demonstrated that the thermal gradient of a partially impregnated prepreg affects the rate of impregnation and gas transport during consolidation. The Cycom 5320-1 epoxy system was used for the investigation. Porosity distribution is shown to be influenced by the thermal gradient. Areas with hotter-than-average temperatures prevented air from evacuating the laminates. The study reported that resin flow, permeability, bubble transport, and temperature evolution affected air evacuation. Other parameters such as prepreg formats may affect laminates produced with VBO prepregs. Maguire et al. [36] investigated the importance of prepreg formats and the manufacturing method for VBO prepregs. Manually applying epoxy powder may lead to non-uniform powder distribution, which could produce better laminate uniformity. The study confirmed that epoxy powder prevents an exotherm reaction in thick composites. However, the temperature cycle and latency of the epoxy powder need to be optimized for the best results. How the epoxy powder propagates heat within the VBO prepreg was unclear to the authors; hence further investigation is required. In another study, Edward et al. [37] designed a unidirectional semi-prepreg that improved the robustness of VBO processing. A toughened epoxy resin was used. The semi-prepreg was customized to discontinue resin distribution. As a result, through-thickness permeability was improved, which facilitated gas evacuation. Laminates produced by the semi-prepreg had fewer defects than those produced by conventional VBO prepregs. The resin feature morphology was observed to be critical in defect formation.

5. Resin Transfer Molding (RTM)

The RTM process involves using a closed mold to fabricate a composite part. Fiber preform is cut according to the mold shape and placed in a closed mold cavity [38]. A low-viscosity thermoset resin is injected through the injection port into the mold cavity, usually with a 3.5–7 bar pressure. The injected resin impregnates the preform evacuating entrapped air bubbles until complete wetting is reached. Once the resin starts exiting from the vent ports, the resin injection is stopped, and vent ports are closed. The resin is allowed to cure by heating the mold or the initial addition of inhibitors to the resin system. After the resin is cured, the mold is opened, and the part is de-molded. Some variants of the RTM process are VIPR, FASTRAC, light RTM (LRTM), structural reaction injection molding (S-RIM), and co-injection resin transfer molding. Some advantages of RTM are that the process can produce parts with close dimensional tolerance and an improved surface finish. Parts made by RTM have a high-volume fraction of about 60–70%. RTM can manufacture complex-shaped composite parts. Consistent reproducibility of composite parts can be achieved using the RTM process. Due to high resin pressure and faster mold opening and closing, a fast-manufacturing cycle is reached, further improved by process control. Some drawbacks of the RTM process are the limited size of parts that can be manufactured. Fiber wash can occur due to high resin pressure and loose fiber compaction. Furthermore, improper location of injection gates and vents can lead to a macro void in the composite [39].

6. Vacuum Assisted Resin Transfer Molding (VARTM)

In the VARTM method, the reinforcement is placed on a one-sided mold and sealed with a vacuum bag to form a closed mold. A vacuum is applied at the vent, which drives the resin under atmospheric pressure to impregnate the reinforcement while evacuating the air bubbles and compacting the fiber preform. The resin flows through the porous preform and arrives at the vent. The injection is closed, but the vacuum is maintained until the part is completely cured and de-molded. The VARTM process is used to produce large composite parts at a low cost with a low production volume [40]. This process is widely used in the energy, aerospace, marine, defense, and infrastructure building industries [41]. Variations of VARTM have been invented to cater to the manufacturing of complex parts with better quality at a reduced cost. The VARTM process has some advantages: flexibility of mold tooling and selection of mold materials [42], resin and catalyst can be stored separately and mixed before infusion, low emission of volatile organic compound (VOC), and visible inspection of the process to identify and manage dry spot occurrence [43]. However, some drawbacks of this process are that consumables such as sealing tape, peel-ply, and vacuum bags may not be reusable. The low resin injection pressure can limit void compressibility resulting in high void content and low fiber volume fraction. The process may be susceptible to high chances of air leakage, depending on the operator’s skill level [44].

7. Quickstep Curing

In the quickstep process, prepregs are stacked up in a one-sided mold to form a laminate and sealed with a vacuum bag. The laminate-mold assembly is placed inside a pressure chamber supported by two flexible membranes. A heat transfer fluid (HTF) system controls the laminates’ temperature and regulates resin viscosity by circulating the HTF through the pressure chamber [45]. The HTF, with high heat capacity and thermal conductivity, maintains a rapid heating and cooling rate as low pressure of 10 kPa is applied [46]. To further increase the laminate compaction and reduce voids, an alternating pressure is applied to the HTF. The quickstep process reduces the curing cycle, capital, tooling, and operational costs. Furthermore, the quickstep can fabricate medium composite parts of high quality. Nevertheless, the fact that the heat transfer system solely depends on fluid can be a disadvantage. The quickstep process may be restricted to medium complexity parts because of the low applied pressure. The flexible membrane has a limited life span [47]. Numerous studies have demonstrated the use of quickstep curing to fabricate laminate panels that are comparable to panels produced by the autoclave [48] and better than those produced by hot press and oven cured [49]. Enhanced composite properties made by quickstep are attributed to fiber bridging, consistent curing, and improved fiber/matrix adhesion in quickstep techniques [49].

8. Seeman Composite Resin Infusion Molding Process (SCRIMP)

The SCRIMP process is a modification of the VARTM process. It is an improved version of the VARTM process to efficiently and effectively distribute resin during impregnation using a distribution media (DM). Therefore, it is used for making high-quality and repeatable parts with minimal volatile emissions. Composite parts made by the SCRIMP process have a high fiber volume fraction typical of about 60–75% [50]. The DM is a highly permeable material placed between the vacuum bag and the topmost layer of the fabric [51]. It helps to distribute the resin quickly, thereby reducing the fill time. The resin initially flows through the DM layer before wetting the reinforcements through the thickness direction. A second type of resin distribution system exists in SCRIMP [52]. The groove-based SCRIMP incorporates channels in either the core or mold, and the resin is first delivered to the channels and then to the fiber mat. Ni et al. [53] reported the mold filling of SCRIMP based on the groove to be much faster than SCRIMP based on a highly permeable medium. This process is used to make lightweight truck components, heavy-duty buses, large yachts, bridges [54], and naval vessels.

9. Resin Film Infusion (RFI)

In the RFI process, one male or one female mold of the desired shape is used [55]. A thin film of neat resin is interleaved with layers of fibers and placed in the mold. The lay-up assembly is vacuum bagged, and the air is removed with a vacuum pump [56]. The lay-up assembly is then placed inside an oven or autoclave for curing. When the mold is heated and pressurized, the resin melts, flows into the fibers, and is then cured. The cure cycle is carefully selected to achieve the proper time-temperature-viscosity profile to ensure proper fiber saturation [57].

10. Resin Infusion under Double Flexible Tooling (RIDFT)

The RIDFT process is a variation of the liquid composite molding (LCM) technique. The RIDFT idea was developed to solve problems existing in other LCM processes. Some of these issues are high tooling costs, slow production rates, complex resin infusion, long processing times, usage of an expensive preform, and environmental pollution [58]. The RIDFT process uses a two-dimensional resin flow to produce cost-effective composite parts at an increasingly higher production rate while reducing volatile organic compound emissions into the environment. Fiber reinforcements are initially placed between the two silicone diaphragms and closed (step 1). Air is vacuumed from between the two silicone sheets via the vent port to compact the fiber reinforcement, and therefore, permeability is reduced (step 2). Once the resin infusion gate is open, vacuum pressure drives the resin from the reservoir to impregnate the fiber reinforcement (step 3). A flow distribution media is placed on top of the silicone sheets to increase permeability and assist in the quick infiltration of the resin. After impregnation, the infusion gate is closed, and the wetted reinforcement inside the silicone sheets is draped over a one-sided mold with the aid of a vacuum [59] (step 4). At this time, the vent port is still left open. The formed part is allowed to cure, after which it is de-molded (step 5). Using a silicone sheet prevents the direct contact of the wetted reinforcements on the mold, which increases the tool life [60]. However, silicone sheets are expensive to replace, and cleaning them during production runs between parts takes longer.

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