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INFLUENCE OF THE STABILIZING BINDER ON VOID CONTENT IN THICK WCM NON-CRIMP FABRIC COMPOSITE PARTS

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ABSTRACT

Wet Compression Molding (WCM) processes have recently drawn the attention of the automotive industry as a potential replacement for High-Pressure Resin Transfer Molding (HP-RTM) processes, which require costly equipment and additional tooling for fabric preforming. However, manufactured WCM parts may be susceptible to defects such as voids or dry regions, particularly for thick parts with complex geometries where a binder stabilized fabric may be used. The goal of this study was to investigate the influence of stabilizing binder on the formation of voids in non-crimp fabric carbon fiber/epoxy composite parts fabricated using a WCM process. Flat panels were manufactured with different fabric conditions, including unbindered, bindered without pre-activation, and bindered with pre-activation, and with or without the use of a vacuum. Samples were extracted from these panels and prepared for microscopic assessment to qualitatively assess voids within the parts. Voids were observed regardless of the presence of stabilizing binder or binder pre-activation; however, the number of voids was minimized by applying vacuum to the mold. Preliminary results showed that the presence of a stabilizing binder may influence the size of the voids.

1 INTRODUCTION

Wet Compression Molding (WCM) with highly reactive resins is a manufacturing process with a mass-scale production potential that has been adopted recently in the automotive industry and is becoming an alternative to the established High Pressure Resin Transfer Molding (HP-RTM) process [1]–[3]. The WCM process has two different variants, namely direct and indirect as shown in Figure 1. The difference between these two variants is the moment when the forming occurs. For this study, the direct variant was performed, which consists of fabric cutting, resin application, introduction of the impregnated fabric into the mold, forming, curing, and demolding steps. The direct variant of the WCM represents a more economical option compared to HP-RTM due to the simultaneous draping and curing of the part, which eliminates the need for a preforming tool [2]. Nevertheless, thick WCM parts with complex geometries may require use of a binder stabilized fabric to improve resin management during the process.

The WCM process is distinguished by a lower compaction force and mold pressure in comparison to the HP-RTM process. As a result, the pressure within the fabric layers may be lower than the vapor pressure of moisture present between the layers and acting in opposition to the resin pressure [4]. This pressure difference may form voids inside the parts, which is one of the main challenges of the WCM. Fels et al. [2] conducted an investigation comparing WCM and HP-RTM processes where multi-directional non-crimp fabric (MD-NCF) was used. The authors found that although WCM parts exhibited higher volume content and therefore lower interlaminar shear strength, the WCM and HP-RTM parts exhibited similar in-plane mechanical properties.

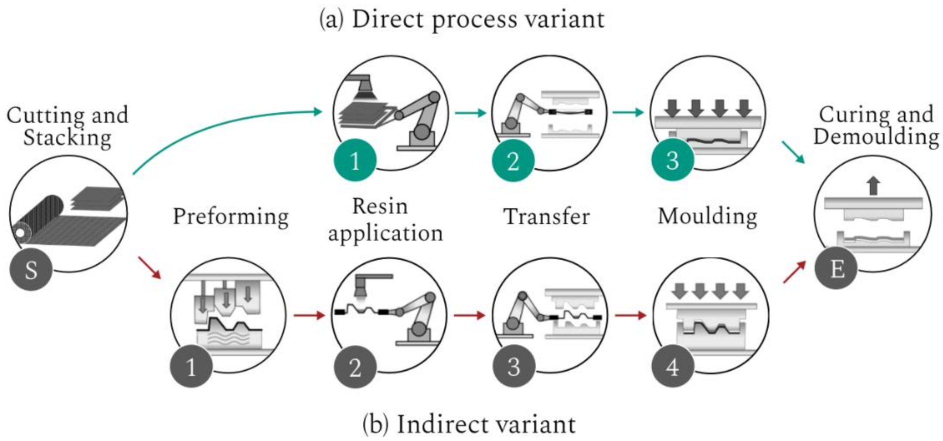

Figure 1. Schematic of the WCM flow variants [4].

The goal of this study was to investigate the influence of stabilizing binder on void content in WCM unidirectional non-crimp fabric (UD-NCF) composites. Flat panels were manufactured with 8 layers of carbon fiber UD-NCF and snap-cure epoxy resin, where the fabric conditions were varied from unbindered, bindered without pre-activation, and bindered with pre-activation and a vacuum was used to draw air from the mold for some panels. To verify the presence of voids within the manufactured panels, samples were extracted from each WCM panel and assessed microscopically.

2 EXPERIMENTAL PROCEDURE.

2.1 Materials

Two carbon fiber UD-NCFs were used to manufacture flat panels via WCM, namely PX35-UD300 (Zoltek, US) either with or without a stabilizing powder binder. The details of the UD-NCF is given in [5], [6]. A three-part snap-cure epoxy resin, Epikote 6150 (Westlake Epoxy, US), was used.

2.2 Tooling and Equipment

A $304.8\ \mathrm{mm} \times 304.8\ \mathrm{mm}$ two-part mold mounted to a 100-ton press with integrated platen heating and a metering unit to rapidly mix and dispense resin was used to fabricate flat panels. The upper mold half had a vacuum port which was used to connect to a vacuum pump to draw air out of the mold prior to mold closure for a subset of the fabricated panels (Figure).

2.3 Flat Panel Production by WCM

The production of flat panels using the WCM process involved the stacking of 8 layers of UD-NCF (i.e., a $[0_8]$ laminate), each measuring $300 \times 300\ mm^2$. Next, the resin components were introduced to the metering unit tanks, the resin was poured with the additive into a heated tank, while the hardener was poured into the other tank. The metering unit rapidly mixed and dispensed the different parts of the resin system onto the center of the fabric stack through a static mixer, after to transferring the stack into the pre-heated mold. The temperatures of the lower and upper mold halves were $135°C$ and $115°C$, respectively, and the force applied by the press was set to achieve a mold pressure of 30 bar. The resin was allowed to cure for 5 minutes under full pressure, prior to demolding the part without any temperature cooldown. Table 1 outlines the panels manufactured by the WCM process, including two panels comprising unbindered fabric, two panels with fabric comprising an inactivated stabilizing binder, and subsequent panels where the binder was activated in a convection oven at $120°C$ for 20 minutes. Only the final two sets of panels underwent vacuum application for durations of 20 and 40 seconds, respectively. Table 1 also presents the average thickness of each configuration.

Table 1. Panels manufactured by WCM process.

Panel	Stabilizing Binder	Vacuum	Quantity	Thickness [mm]
Configuration 1	No	No	2	2,43
Configuration 2	Not pre-activated	No	2	2.33
Configuration 3	Pre-activated	No	2	2.30
Configuration 4	Pre-activated	20 s	2	2.30
Configuration 5	Pre-activated	40 s	2	2.20

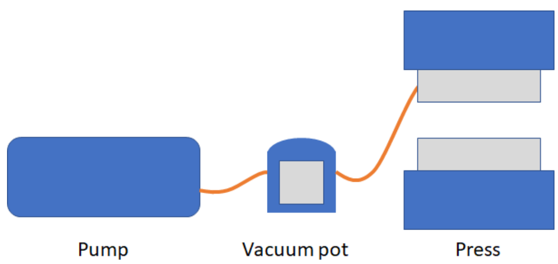

Figure 2: WCM process manufacturing scheme.

2.4 Microscopic Assessment

To conduct the microscopic assessments, samples with dimensions $20\ \mathrm{mm} \times 20\ \mathrm{mm}$ were waterjet cut from the panels. These samples were taken from the central region of the panels corresponding to the location where the resin was dispensed onto the fabric stack (Figure 3). Each sample was cold mounted in a cylindrical silicon mold with epoxy.

The final cold mounted samples were sanded and polished following a four-stage procedure: “Primo 120” (coarse grinding) with water for 3 minutes, “Allegro” (fine grinding) with diamond solution DiaPro Allegro/Largo 9 for 6 minutes, “Dac” (coarse polishing) with diamond solution DiaPro Dac 3 for 6 minutes, and “Nap” (final polishing)

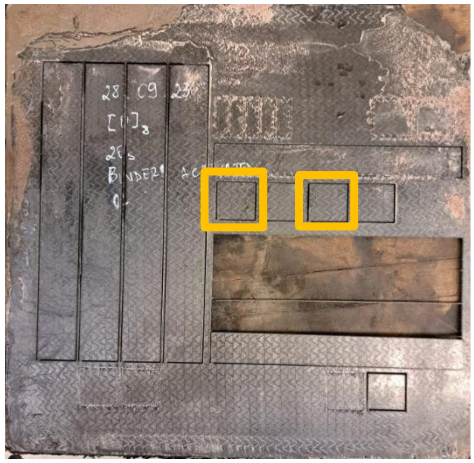

Figure 3: Flat panel fabricated using the WCM process with the locations where samples were extracted indicated by orange boxes.

with diamond solution DiaPro Nap B1 for 3 minutes. After the preparation procedure, each sample was assessed with a Keyence WHX-5000 opto-digital microscope equipped with a 500-5000x lens.

3 RESULTS AND DISCUSSION

Figures 4, 5 and 6 illustrate the microscopic images of the samples from configurations 1, 2, and 3, respectively. Comparing configurations 2 and 3, it can be noted that when stabilizing binder is activated, the system prevents the fabric layers from moving relative to each other, resulting in a visually more consistent layer thickness (indicated by the black arrows) compared to the panel with non-activated binder fabric layers. For configurations 1 and 2, the layer thickness varied across the length of the panel. In configuration 1 (Figure 4), a significant number of small voids were visualized. Most of those voids can be classified as intra-tow voids (highlighted in dark red) and are concentrated in the half of the sample that sits on the lower mold half. Similarly, for configuration 2 a significant number of intra-tow and some inter-tow voids (highlighted in purple) were observed. However, the voids present in configuration 2 are slightly larger, although the width of the voids for both configurations fall within a similar range (up to $300\ \mu m$). In addition, the void content is more spread through the thickness in configuration 2 compared configuration 1. Similar to configuration 2, configuration 3 also exhibits a significant number of voids more concentrated in the lower half of the panel thickness, but the void content is more spread through the thickness than configuration 1.

The higher void content observed in the bottom half of the panels is attributed to the air trapped within the fiber tow near the bottom surface of the part, which the resin was unable to expel. Configurations 2 and 3 present cases in which the binder melts and coats the fibers, which may influence resin flow and void formation. Note, the resulting number of voids and their size was similar for configurations 2 and 3.

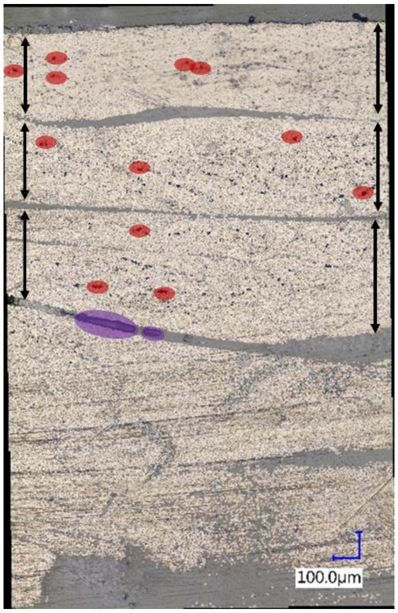

Figure 4: Microscopic image of the cross-section of a sample comprising unbindered fabric (configuration 1).

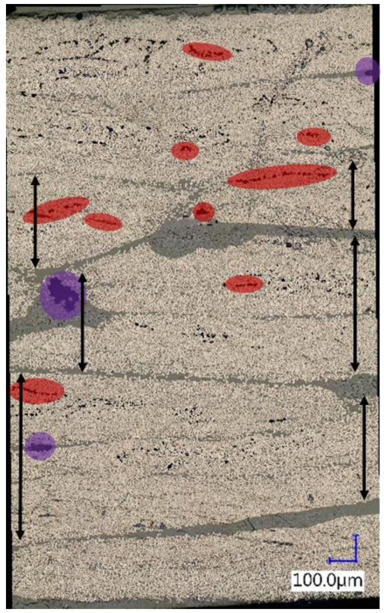

Figure 5: Microscopic image of the cross-section of a sample comprising inactivated bindered fabric (configuration 2).

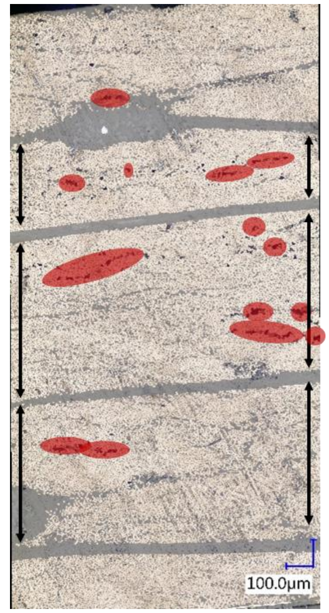

Figure 6: Microcopic image of the cross-section of a sample comprising pre-activated bindered fabric (configuration 3).

Figures 7 and 8 show the microstructure of the configurations 4 and 5, respectively. It can be seen in both figures that by applying vacuum to the mold, the number of voids is reduced when compared to panels where the vacuum was not used. The reason to improve the quality of the samples by applying vacuum to the mold is the removal of air trapped between the layers and within the fiber tows. From the images shown below, it is possible to conclude that 20 seconds is enough to vacuum the air inside the mold. However, it was noticed that the thickness of the samples from configuration 5 exhibited a more consistent thickness measurement and were 4% lower than the measurements from configuration 4 as presented in Table 1. Comparing configurations 3 and 4, there is no statistical difference between their thickness average. Therefore, between the three configurations (3, 4 and 5), the fiber volume fraction should be like the third and fourth configurations, but the fifth may exhibit a fiber volume fraction 4% greater than the previous ones.

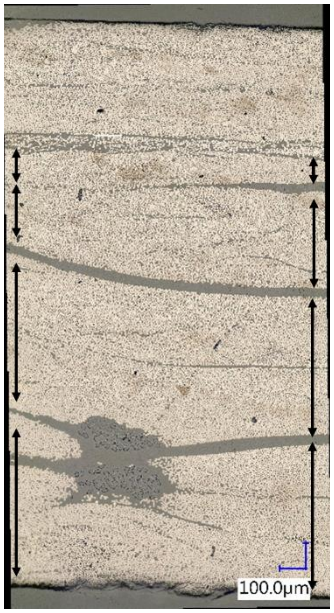

Figure 7: Microscopic image of the cross-section of a sample comprising pre-activated bindered fabric with 20 s applying vacuum.

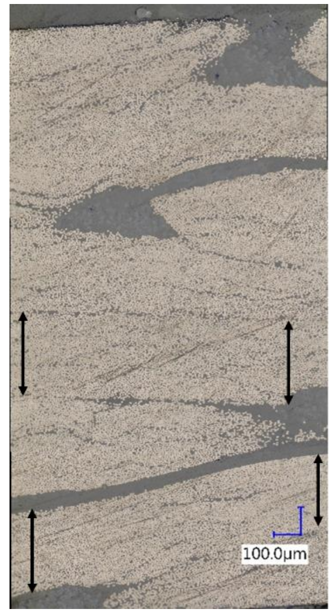

Figure 8: Microscopic image of the cross-section of a sample comprising pre-activated bindered fabric with 40 s applying vacuum.

4 CONCLUSION AND SUMMARY

The analysis of the extracted sample images reveals a consistent occurrence of voids in both parts with and without a stabilizing binder when a vacuum was not applied. There is a higher concentration of voids in the bottom half on the part, which may indicate a challenge regarding the number of layers and, consequently, the thickness of the final part. Additionally, the increase in viscosity during the draping process contributes to this issue. The number of voids was minimized by applying vacuum to the mold, removing the excess air trapped between the fabric layers and within the fiber tows. In conclusion, the presence of stabilizing binder presented little influence on the presence of voids, as the unbindered fabric also presented a significant number of voids; however, the stabilizing binder presents influence on the size of the voids. The alternative to minimize the void content is by applying vacuum to the mold for a short period of time.

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