HIGH PRESSURE COMPRESSION RTM - A NEW PROCESS FOR MANUFACTURING HIGH VOLUME CONTINUOUS FIBER REINFORCED COMPOSITES

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Abstract

The current paper addresses High Pressure Compression Resin Transfer Molding (HP-CRTM) for the manufacturing of continuous fiber reinforced composites with high fiber volume content. The HP-CRTM process is a combination of resin transfer molding (RTM) and compression molding. In this process, the preform is placed into the mold cavity and then the mold is closed partially to obtain a small gap between the mold surface and the fiber preform. The resin is introduced through a suitable injection point into the gap and flows easily over the preform and may partially impregnate the preform as well. Once the required amount of resin is injected into the gap and the injection point is closed, the mold closes further and applies high compression pressure to squeeze the resin into the preform. In this step, the preform is compacted to achieve the desired part thickness and fiber volume fraction. The objective of the proposed study is to investigate the effects of parameters such as mold opening distance and fiber orientation on the quality of the HP-CRTM components. The influence of these process variables on the component quality and the mechanical properties is analyzed. Finally the applicability of the HP-CRTM process for high volume manufacturing is discussed.

Introduction

Classical RTM Process

The resin transfer molding (RTM) process is well established for low volume manufacturing applications and has recently gained great interest in the manufacturing of higher volumes. This interest is strongly motivated by the need of lightweighting for the automotive and aerospace industries. The classical RTM process in its current status, however, is limited by the low volume production capacity of the preforming processes, long impregnation time and lack of robust injection equipments. These issues hinder the use of RTM process for high volume manufacturing of the components. Figure 1 shows the injection sequence in the classical RTM process. The three dimensional preform is placed into the cavity and the mold is completely closed. The mold closure leads to compaction of the preform to the final part thickness thereby leading to reduction in the preform permeability. The reactive resin (premixed thermoset resin and hardener) is then injected into the cavity under pressure which is typically 1 to 20 bar [1]. The resin flows along the length of the preform and impregnates the fibers. Ideally, once the impregnation process is completed the resin undergoes a curing reaction and after a defined time interval, the part can be demolded.
The complete closure of the mold prior to the resin injection leads to reduction in the permeability of the preform, hence resulting in longer resin injection and preform impregnation time. Longer impregnation time in the classical RTM process does not allow for use of fast curing resins for high volume manufacturing of the RTM components. An alternative approach to obtain high permeability in the mold during resin injection can be obtained by using the CRTM process which is illustrated as below.

### CRTM Process

The resin injection sequence in the Compression RTM (CRTM) process is illustrated in figure 2. In the CRTM process the dry three dimensional preform is placed in the mold cavity and the mold is closed partially to obtain a small gap between the mold surface and the fiber preform. The resin is introduced through a suitable injection point into this gap and flows easily over the preform and may partially impregnate the preform. Once the required amount of resin is injected into the gap and the injection point is closed, the mold closes further thereby squeezing the resin into the preform. In this step the preform is compacted to achieve the desired part thickness and volume fraction. The part can be demolded after the resin has cured [2].
Parameters Affecting the CRTM Process

Various studies have been conducted by different researchers to investigate the effect of certain CRTM process parameters on the quality of manufactured laminates. Kang et al. has attempted to analyze the CRTM process by studying the experimental and numerical data. Experiments were performed using a vinylester resin and complicated three dimensional preform based on continuous randomly oriented glass fiber mats. The resin was injected into the cavity in 30s and had a gel time of approx. 9 min. The achieved fiber volume content in the CRTM parts was approximately 17%. The varied process parameters were compression force and compression speed. A close agreement was found between the experimental and numerical data by Kang et al [3]. The effect of mold gap and gap closure speed on the void content and flexural properties of the CRTM laminates was investigated by Ikegawa et al. However the used compression pressure and the cavity pressure were significantly low and varied between 1 to 13 bar. The fiber volume content in the produced laminates was 33% [4]. Chang et al. investigated the effect of injection pressure, mold gap, resin temperature, compression pressure, mold temperature and curing temperature on the CRTM process. Experiments were performed using epoxy resin and bidirectional woven glass fabric and obtained fiber volume content in the laminates was approximately 40%. However the used compression pressure was once again very low and it was varied between only 1 to 2 bar [5].

Based on the available literature, it was found that most of the studies for CRTM process used low cavity pressure and low fiber volume content. For the current CRTM process study it was defined that high compression pressure was to be used and also to obtain laminates with high fiber volume content to study the CRTM process further. The process will be referred to as High Pressure Compression RTM (HP-CRTM) process during further discussions in this paper. The mold gap and fiber orientation were varied as the process parameters. A process parameter matrix was defined in such a way that the effect of these parameters on the HP-CRTM process and quality of the laminates could be evaluated. The goal was set to use high fiber volume content (glass fiber content more than 50 vol.%) in the HP-CRTM process and to study the effect of relatively high compression pressure to achieve good quality impregnation. Similar studies have been conducted earlier to evaluate the effect of process parameters on the HP-CRTM laminate properties manufactured by using high compression pressure. The reactivity of the chosen resins was, however, significantly low [6, 7]. The goal of the current study is to use a fast curing resin system to evaluate the effect of process parameters on the HP-CRTM laminate properties, as well as to demonstrate high volume production capability of such a process.

Materials

For the current HP-CRTM process study, an epoxy resin with trade name Araldite LY 564 was chosen. An amine based curing agent with trade name XB 3458 was used to cure the epoxy resin. As reinforcement UD non woven E-glass fabric from SAERTEX GmbH & Co. KG was used. The commercial product number of the chosen glass fabric was S14EU960-01210-01300-487000 and was available with multi-compatible sizing. The used UD non woven glass fabric had a surface area weight of 1218 g/m² with 95% fibers in 0° orientation and 4.5% fibers in 90° orientation as well as additional 0.5% PES based stitching fibers.
Processing Equipments

A RTM mold with cavity size 830 mm x 210 mm x 3 mm and an obligatory shear edge was used for the HP-CRTM process study. The mold had an injection point in the middle of the mold from the lower side. Additionally, the mold facilitated two points on either side of the mold for applying vacuum during resin injection or as an exit port for the extra amount of the injected resin. A hydraulic compression press from the company Dieffenbacher GmbH (press type - DYL630/500) was used to mount the RTM mould as well as to precisely apply defined compression force and to control the mold gap and gap closure speed during the HP-CRTM process study. For the mixing of the chosen epoxy resin and curing agent and for injecting the reactive resin into the mold cavity HP-RTM, equipment from the company KraussMaffei Technologies GmbH was used.

Process Parameter Matrix for HP-CRTM Process Study

*Table I: Process parameter matrix used for the HP-CRTM process study*

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>HP-CRTM 1</td>
<td>60</td>
<td>365</td>
<td>60</td>
<td>1</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>HP-CRTM 2</td>
<td>60</td>
<td>365</td>
<td>60</td>
<td>2</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>HP-CRTM 3</td>
<td>60</td>
<td>365</td>
<td>60</td>
<td>1</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>HP-CRTM 4</td>
<td>60</td>
<td>365</td>
<td>60</td>
<td>2</td>
<td>0.2</td>
<td>5.5</td>
</tr>
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</table>

Table 1 summarizes the process parameters used for studying the HP-CRTM process. Two different fiber orientations (UD and 0/90) were used for studying the HP-CRTM process. Mold gaps of 1 mm and 2 mm were used for manufacturing the laminates for each fiber orientation. For each fiber orientation, 4 layers of reinforcing fabric were used, i.e. for manufacturing UD laminates, 4 layers of glass fabrics were used in 0° orientation and for manufacturing bidirectional laminates ([0/90], orientation) the glass fabrics with a layup of 0/90/90/0 were used. After reinforcing fabric was placed into the mold, the mold was closed using the hydraulic press to obtain a mold gap of either 1 mm or 2 mm. A predefined amount of resin, 365 g, which is slightly higher than the precisely calculated resin amount required for impregnating 4 layers of reinforcement and filling free volume of the injection runner was injected into the partially open cavity using the HP-RTM equipment. The injection time for all the HP-CRTM experiments was set to 5.5 s. After the resin was injected into the partially open cavity, the mold was closed completely at closure speed of 0.2 mm/s, applying 60 bar cavity pressure to obtain a preform compaction and its impregnation by the resin. Hence, the mold closure took approximately 5 s at 1 mm mold gap and 10 s at 2 mm mold gap. Also, it is noteworthy to mention that during the HP-CRTM experiments, the exit port/vacuum port was kept completely closed and no vacuum was applied. The resin was able to flow between the mold plates and the air could escape through the parting line. Hence no exit port was necessary to allow degassing during processing. The mold was heated to 100°C to obtain optimum cure kinetics of the chosen epoxy resin and to achieve a demolding time of 4 min. For each process study, at least 5 laminates were manufactured to evaluate the process reproducibility and to characterize the laminates manufactured by different process parameters.
Materials Characterization

The manufactured laminates were tested using following norms:

- DIN EN ISO 7822 for characterization of the fiber volume content
- DIN EN ISO 527-5 for characterization of the tensile properties
- DIN EN ISO 14125 for characterization of the flexural properties
- DIN EN ISO 14130 for characterization of the inter-laminar shear strength (ILSS)

Results and Discussion

Determination of Impregnation Behavior

At the start of the HP-CRTM process study, the degree of mold filling after resin injection in partially open mold gap and before compression step was determined for the defined fabric layup and mold gap. Picture 1 and picture 2 shows the degree of mold filling for 365 g of injected resin amount at 1 mm and 2 mm mold gap for unidirectional and bidirectional laminates respectively. As it can be seen from the pictures, at 2 mm mold gap, the resin covers approx. 70% of the mold surface and also impregnates the fabrics partially over this area for both the fabric layups. At 1 mm mold gap the resin covers almost 100% of the mold surface and impregnates the fabrics partially.

![Picture 1](image1.png)

(a) (b)

*Picture 1: Degree of mold filling after injection and before compression in the HP-CRTM process for unidirectional laminates (a) at 2 mm mold gap; (b) at 1 mm mold gap*

![Picture 2](image2.png)

(a) (b)

*Picture 2: Degree of mold filling after injection and before compression in HP-CRTM process for bidirectional laminates (a) at 2 mm mold gap; (b) at 1 mm mold gap*
From the analysis of the degree of mold filling before compression step, as shown in picture 3, two different sections of the HP-CRTM laminates can be identified in terms of their impregnation behavior. At 1 mm and 2 mm mold gap, the section 1 is partially impregnated after resin injection step and prior to the compression step. In case of 1 mm mold gap, the resin covers almost the complete surface of the mold after resin injection. Application of compression pressure therefore leads to compaction of fabrics as well as further impregnation of the fabrics in Z direction in section 1 due to almost no flow of resin along X and Y directions. In case of 2 mm mold gap, application of compression pressure leads to compaction of fabrics as well as further impregnation in the section 1. It also leads to impregnation of dry fabrics in section 2 due to resin flow in X and Y direction occurring from additional resin being squeezed out from section 1.

For characterization of the HP-CRTM process these differences in the impregnation behavior were taken into account and the impregnation quality of the laminates produced at 1 mm mold gap and 2 mm mold gap was studied by characterization of the ILSS properties in section 1 and section 2.

Fiber Volume Content in the HP-CRTM Laminates

![Fiber Volume Content Graph](image-url)

*Figure 3: Part thickness and fiber volume content in HP-CRTM laminates*
Figure 3 shows the effect of the used mold gap on the final part thickness and fiber volume content in the unidirectional and bidirectional laminates manufactured using 1 mm and 2 mm mold gap. As it can be observed, at each mold gap and fabric layup, laminates of nearly constant thickness were obtained indicating same degree of compaction of the preform during compression at both the mold gaps. The laminates showed equivalent fiber volume content in the range of 56% to 58%. Figure 3 shows the average values of the fiber volume content measured from samples taken from section 1 and section 2. The part thickness was higher than 3 mm, indicating that the upper and lower mold edges had no contact to each other during laminate manufacturing and the compression pressure of 60 bar was applied on the resin and fabrics during laminate manufacturing indicating impregnation of the laminates was carried out under 60 bar cavity pressure.

**Tensile Properties of the HP-CRTM Laminates**

The samples for tensile testing were taken from the section 1 of the HP-CRTM laminates. Figure 4 shows the tensile properties of the HP-CRTM laminates. For each fabric layup, the selection of mold gap of 1 mm or 2 mm exhibited similar tensile properties. This shows that during HP-CRTM process the application of the high compression pressure leads to no displacement of the layers or fiber rovings in the final laminates.

![Tensile properties of HP-CRTM laminates](image-url)
Flexural Properties of the HP-CRTM Laminates

Similar to the tensile samples, the flexural samples were also taken from the section 1 of the HP-CRTM laminates. Figure 5 shows the effect of the mold gap on the flexural properties of the unidirectional and bidirectional laminates. It can be seen that the flexural properties of the bidirectional laminates, though with 50% fibers in 90° orientation, are significantly high. This can be explained on the basis of the used laminate layup for the bidirectional laminates. As the bidirectional laminates had a symmetric layup ([0/90]_s) with 0° layer on the top and the bottom the flexural properties were significantly higher. It was noticed that for unidirectional and bidirectional laminates, the measured flexural properties at 1 mm and 2 mm mold gap were almost identical to each other, indicating nearly equivalent impregnation quality of the HP-CRTM laminates in section 1 for these two different mold gaps.

![Figure 5: Flexural properties of HP-CRTM laminates](image-url)
ILSS Properties of the HP-CRTM Laminates

Figure 6: Fiber volume content in different sections of HP-CRTM laminates

The ILSS properties of the HP-CRTM laminates were measured at two different locations on the laminates. Samples were taken from the section close to the injection point (section 1). The second set of samples was taken from the section at a significant distance away from the injection point (section 2). Figure 6 shows the fiber volume content of the HP-CRTM laminates measured in these two different sections. As it can be seen from figure 6, higher fiber volume content was detected in the section away from the injection point for 1 mm and 2 mm mold gap. The higher fiber volume content measured in the section away from the injection point, in comparison to the lower fiber volume content measured in the section near to the injection point, at same laminate thickness, indicates that higher void content may be present in the laminates section away from injection point.
Figure 7: ILSS properties of HP-CRTM laminates

Figure 7 shows the ILSS properties of the unidirectional and bidirectional laminates. Similar to the tensile and flexural properties, the ILSS properties of the unidirectional and bidirectional laminates were not influenced by the mold gap. Not only this, but the ILSS of the samples taken from section 1 are equivalent to ILSS of the samples taken from section 2. Though it was found that the fiber volume content in section 1 was approximately 2% lower than fiber volume content in section 2 at 2 mm mold gap and also for similar position of the samples for 1 mm mold gap, the measured ILSS values in these two different sections at constant layup are identical to each other at both the mold gaps. Hence it is difficult to come to any conclusion on the quality of impregnation in these two different sections of the HP-CRTM laminates. Further investigations are essential to determine the void content in these two different sections of the laminates.
Summary

The effect of the mold gap and the fiber orientation on the quality of the laminates manufactured by the HP-CRTM process was studied. The mold gap was varied by a value of 1 mm and 2 mm whereas for an UD non crimp glass fabric product, the unidirectional and bidirectional fabric layups were used. A fast curing resin system with cure cycle time of approx. 4 min was used for the HP-CRTM process study. In the HP-CRTM process, the resin injection was completed in 5.5 s and the mold was closed in approximately 5-10 s leading to completion of impregnation of reinforcing fibers by the resin. Hence in the HP-CRTM process the resin injection and impregnation of fibers was conducted in approximately 10 s to 15 s which is significantly shorter. This clearly indicates the advantage of the HP-CRTM process and presents an alternative approach to reduce the required resin injection and impregnation time and combining this advantage with the fast curing resin systems for high volume manufacturing of the continuous fiber reinforced composites. Also the properties of the HP-CRTM laminates manufactured at 1 mm and 2 mm mold gaps were correlated to each other. In principle for the unidirectional and bidirectional laminates, the variation of the mold gap did not show any influence on the tensile, flexural and ILSS properties of the laminates. A small deviation in the fiber volume content of the HP-CRTM laminates was observed in different sections of the laminates.

Outlook

Further investigations are ongoing at Fraunhofer ICT to investigate the effect of the process parameters such as the effect of resin systems, resin viscosities, fabric types on the quality of the laminates manufactured by using the HP-CRTM process. Simultaneously investigations are ongoing at Fraunhofer ICT to setup an automated and industrial scale HP-CRTM process and High Pressure Injection RTM (HP-IRTM) process using KraussMaffei High Pressure RTM equipment.

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