Abstract

The growing demand for the reduction of CO\textsubscript{2} emissions is pushing the OEMs at decreasing car’s weight. Composites are one of the most promising solutions, permitting to combine high mechanical performances with low weight.

Traditional technologies like Vartm or Autoclave, however, are not productive enough to withstand the massive volumes typical of the automotive industry. Average cycle times to obtain CFRP parts, in fact, can easily go beyond two hours, seriously limiting the adoption of these types of materials wherever big volumes are in place.

Thanks to the R&D efforts of both chemical companies and machinery suppliers, however, a whole new way of making CFRP parts are being developed. The paper presents a review of the main trends in CFRP mass production technologies from an equipment perspective and focuses on how to combine stacking preforming, injection and pressing technology to achieve production lines for HP-RTM, Wet Pressing and Compression molding of Thermosetting composites (Prepreg, SMC and Hybrid parts).

Introduction

Composites in automotive come straight from the call of governments all around the world for emissions reduction. As a clear example, Figure 1 shows the regulatory plan that the European Union has set as far as emissions of passenger vehicles are concerned. In 2007, when average emissions expressed in grams of carbon dioxide emitted per kilometer were 160, the EU decided to apply an ambitious target for 2021 of 95 grams of carbon dioxide emitted per kilometer. The plan foresees a penalty of 5€ to be paid per sold car when the average fleet emissions exceed the first gram over the limit; 15€ per sold car for the second gram over the limit; 25€ per sold car for the third gram over the limit and 95€ per gram starting from the 4\textsuperscript{th} gram. [1]

This plan resulted in pressuring OEMs towards emissions reduction. The first effects could be seen in strong efforts in making the powertrain greener. Hybrid technology was a big revolution, together with automatic engine start and stop systems and ultimately, electric cars. More recently though, the revolution has moved towards the main structural components of the car that are being re-engineered in a weight reduction perspective.
Figure 2 shows 23% of a car’s consumption can be allocated to weight. This portion is related to the power used to accelerate the mass of the car (and that will become more and more relevant in the future if we consider the growing dimensions of cities and the theory of Megacities [2]). Re-engineering a car’s chassis in a weight reduction perspective is, therefore, a very good strategy to reduce emissions. The weight reduction emission cutting effect has, in fact, been calculated in 0.08 grams of CO2 per kilogram saved [3].

Composites are becoming more and more part of this re-engineering process thanks to their high structural efficiency. Figure 2 shows a massive weight reduction potential of 50% when a CFRP fender is compared to a steel one. Clearly, however, if composites are to be implemented in a rigid, automated and productive environment like the automotive industry, a whole new set of composites manufacturing technologies have to be developed in order to cope with the challenges of their mass production.
Composites Mass Production Technologies: an equipment-based categorization

When looking at the composites mass manufacturing technologies available on the market from an equipment manufacturer’s perspective, two macro categories can be identified using, as a criteria, the phase of the value chain when matrix and reinforcement are put together:

- **Forming Technologies**: matrix and reinforcement are already combined. The final part is achieved through an activation of the matrix and a subsequent compression molding step where forming and curing take place.
  - Pros:
    - Lower equipment complexity
    - Reduced stock mix
  - Cons
    - Higher raw material cost
    - Higher stocking cost (low temperature)
    - Limited shelf life

- **Impregnate & Form technologies**: matrix and reinforcement are sourced separately. The final part is achieved combining impregnation and subsequent molding steps.
  - Pros
    - Lower raw material cost (impregnation is made in-house)
    - Higher productivity (matrix is mixed and cured in situ and fast reacting chemicals can be used)
    - Ability to fine tune the matrix properties
  - Cons
    - Higher equipment complexity and cost
    - Increased stock mix
    - More challenging quality control

The two approaches result in different manufacturing technologies and, consequently, lead to two separate categories of machineries and lines. The following FOUR examples will be described in the next sections:

- **Impregnate & Form Technologies**:
  - High Pressure Resin Transfer Molding
  - Liquid Compression Molding

- **Forming Technologies**
  - Prepreg Compression Molding
  - Carbon Fiber SMC
High Pressure Resin Transfer Molding (HP-RTM) is the mass production version of the conventional RTM (Resin Transfer Molding) process and makes use of fast curing chemicals (curing times below five minutes). The process consists in the impregnation of a preform with a matrix that is mixed through a mixing head connected to the mold.

The steps involved in HP-RTM, when applied to the mass production of CFRP parts are the following:

**Automatic Stacking**

The stacking phase is necessary to properly prepare the stack of reinforcement layers that will be subsequently preformed. Stacking is achieved through a dedicated automatic line. As a first step, an automatic unrolling system creates the stack in one shot by handling up to 8 rolls in parallel. As a second step, the layers are spot welded through a spot welding station integrated into the line. After welding, a labelling phase takes place in order to trace the stacks along the line. The actual shape is then cut through a 2D cutting machine. The last step is the unloading of the stacks.

**Preforming**

In HP-RTM, the preforming process, traditionally a manual high cycle time operation, has been totally revolutionized in a mass production perspective. Preforming in HP-RTM is a must since it permits uniformity and repeatability of the preforms quality, making possible the automatic handling of the fibers for mold loading operations.

A binder (either thermoplastic or thermosetting) is usually pre-applied to the reinforcement. The process consists, therefore, of two macro phases: heating and forming. The stack is loaded into an oven where the activation of the binder through heating takes place. The hot stack is then transferred to the preforming press. The biggest challenge of the preforming process is by far the transferring of the hot stack from the oven to the preforming press. On one hand, the transfer needs to be fast, not to dissipate the heat that has been generated. On the other, it must be precise to avoid the creation of wrinkles on the preform during the draping and forming phase. An intelligent gripping system has been developed for this delicate transfer operation. The system is made of two bars with multiple hands. Each bar can move along the line independently and can roll thanks to two servomotors that move the bar’s edge. Each hand can move on its axis thanks to servomotors. The system can, therefore, fully and automatically replicate the draping that, for lower volumes, is typically manual activity. Such types of preforming lines can, in this configuration, achieve cycle times lower than one minute and represent the state-of-the-art of automatic preforming technology.
Impregnation and Molding

The Impregnation and molding stage is the heart of HP-RTM technology. The preform is loaded into the molding press and a high pressure injection of liquid matrix takes place. In order to exploit the fast reactivity of the new generation chemicals, the components of the formulation are kept separated and are mixed on demand, when the part needs to be injected. Being the reaction time is very short, the viscosity of the chemical grows significantly within the injection window. This results in a very severe pressure rise into the mold (this phenomenon gives the name to the process). Typical values in the industry go from 50 to 120 bar.

The pressure rise into the mold during the impregnation of the preform is governed by the Darcy’s law that can be formulated as:

$$\Delta P = \frac{L^2 \eta}{2Kt}$$

L is the length of the impregnation path, \( \eta \) is the viscosity of the matrix (that varies within the impregnation process), K is the permeability of the reinforcement (inversely linked to the fiber volume fraction) and it is the time available for the impregnation.

The fact that viscosity grows within the injection window puts big challenges on chemical formulators as far as the rheological behavior of the resins is concerned. The ideal matrix is a very fast curing matrix with a flat viscosity curve during the first seconds (time when the chemical is injected). In other words, the chemical needs to be slow for the very first seconds after mixing and then very fast after a certain time (injection window). Although impressive steps ahead are being made by chemical industry towards this ambitious target, current chemicals still exhibit a growth of viscosity starting from the first seconds that follow the mixing. Therefore, when the injection window needs to be wide (for example in case of
long injections for big parts), a slower chemical needs to be selected. The flowrate of the machine must be kept below a certain limit to avoid the fiber washout effect.

Provided that pressure cannot rise indefinitely (the press that keeps the mold closed has a definite closing force), Equation 1 shows the delicate compromise that needs to be achieved in balancing cycle time, part size and fiber volume fraction. In fact, the following statements can be raised:

- A big part with a high fiber volume fraction is likely to require slow cure resins
- Low permeability reinforcements are difficult to mold with fast reacting chemicals
- Big parts need slow cure resins
- Snap cure resins perform at their best with small parts at low fiber volume fractions

After a first overview of the theory that supports the impregnation of a media with a flow, let’s briefly go through the equipment needed to implement it.
The mixing and subsequent injection of the matrix is performed through a dedicated dosing and injection unit. The unit is designed to bring the chemicals at the required temperature while guaranteeing a proper degassing and to dose at the correct flow and mixing ratio of the components. The machine is equipped with jacketed tanks, diathermic oil thermoregulators and heat exchangers that can bring the components up to 100°C. The tanks are equipped with dedicated vacuum degassing systems to degas the chemicals. The heart of the technology is the mixing head. Inside the mixing head the pressure energy that has been generated with the metering pumps is converted into kinetic energy through dedicated injectors. The injectors’ nozzles are placed into a mixing chamber where two or more streams of chemicals are collided one against the other. The collision generates a very severe turbulence that guarantees a proper mixing. Injection control can be performed following two strategies. The injection can be stopped when a certain resin weight has been poured. Alternatively, the trigger can be the in-mold pressure value and the machine can stop when a certain set point is reached.

An important element of the line is the press. HP-RTM presses must withstand the pressure generated during the injection and the curing phases of the process. Designed and built upon customer’ specifications, they must provide a number of features that are somehow conflicting in terms of final result: a fast opening and closing operation, to reduce the dead times of the cycle, but at the same time a very precise control of the parallelism to guarantee the dimensional constancy of the produced parts.
These two requests can be fulfilled using a short-stroke press with Active Parallelism Control. The short stroke is performed during the last few centimeters of closing, when the upper platen of the press travels at a slower speed (from 1 to 20 mm/sec) than that used for the preliminary closing approach and for the opening phase, usually performed at 400 mm/sec or higher, according to customer’s requirements.

The short stroke press is equipped with two sets of cylinders. One set of long stroke-low force cylinders for the fast approaching movement and one set of short stroke-high force cylinders for the pressing stage. The precise measurement of the position of the four corners of the platens, communicated every 20 milliseconds to the central control of the hydraulic circuit, guarantees a real-time control of the parallelism between the two halves of the mold even in the presence of bulky preforms.

Press dimensions with platens of up to 4.5 by 4 meters, with more than 2 meters vertical draw and 36,000 kN of clamping force have currently been supplied, with possible extension of these sizes according to specific needs. Platen deflection at maximum clamping force is specified at 0.1 mm per meter. Loading of preforms and unloading of large finished parts is facilitated by the use of double shuttling systems, that – performing two operations at the same time – speed up the cycle time, reduce labor and avoid the presence of operators within the press area.

Talking of advantages, when comparing these presses with the classic ones for composites, the users very much appreciate a height reduction of 30% that simplify the layout of their factories, and an overall energy consumption reduced by 20%. Then, a faster cycle time should be mentioned, thanks to the design of the press that, working with a limited volume of hydraulic oil, allows for shorter pressure build-up time. Finally the part-to-part dimensional constancy, not a trivial aspect when dealing with irregular, bulky preforms that can interfere in different ways with the closing stroke of the press: the active control of parallelism in this case helps a lot.

Last but not least, molds for HP-RTM are typically made of steel (to withstand the high shear stresses that carbon fiber can generate on the mold surfaces). Thermoregulation ducts are drilled in order to maintain a uniform temperature that can range between 100 °C and 130°C depending on the curing time that needs to be achieved. They are equipped with vacuum valves in order to evacuate the cavity prior to the injection and to avoid the formation of air bubbles into the matrix that could lead to crack and subsequent delamination in the final part. In HP-RTM, molds are also heavily sensorized. In mold pressure is constantly monitored in order to control the injection. Temperature and resin front can also be sensed by dedicated sensors. Resin front sensors can be useful in controlling the closing of vacuum valves.
Impregnation and Forming Technologies: Liquid Compression Molding

As said in the chapter above, the main limitation of HP-RTM process can be, as the name says, high in mold pressure. As shown in Table I, high in mold pressures can generate high opening forces. High opening forces need high tonnage presses to effectively keep the mold closed and planar. High tonnage presses are capital intensive investments and could undermine the business case supporting the investment in HP-RTM technology.

<table>
<thead>
<tr>
<th>Area [m^2]</th>
<th>Pressure [Bar]</th>
<th>Opening Force [Ton]</th>
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<tbody>
<tr>
<td>4</td>
<td>20</td>
<td>800</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>1600</td>
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<tr>
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<td>100</td>
<td>4000</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>4800</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
<td>5600</td>
</tr>
</tbody>
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Table I: Mold opening force as a function of in mold pressure

Big efforts have been put in trying to minimize the in mold pressure in order to reduce the molding equipment size. The most successful and utilized technology is Liquid Compression Molding, a process where a laminar flow of liquid matrix is poured over the reinforcement out of the mold.

The process has the following main advantages:

- Reduced in mold pressure: the impregnation is mostly happening in Z direction minimizing the effect of flow path length on pressure (thickness is smaller than part length and width). Pressure generated during the impregnation is, therefore, never higher than 20Bar for fiber volume fractions in the 40-50% range.
- Flexibility on the reinforcements: a dual aspect of the reduced in mold pressure is that low permeability reinforcements can be easily impregnated and molded.
- Increased productivity: impregnation is done outside of the mold. This means that it can be parallelized with curing. When molding, for instance, a 2m x 2m roof with 2mm thickness injecting at 70g/s targeting a fiber volume fraction of 50% and using a 5minutes curing system, this means to save about 57s of filling time (16% of cycle time).

The limit of Liquid Compression Molding process is that it is not suitable for 3D shapes. The resin cannot be easily and firmly laid down over out of plane surface. HP-RTM remains, therefore, the choice when complex geometries are in place.
Table II summarizes the main properties of HP-RTM and Liquid Compression Molding in relation to geometry complexity, low permeability reinforcements moldability and productivity.

<table>
<thead>
<tr>
<th></th>
<th>PRODUCTIVITY</th>
<th>LOW PERMEABILITY</th>
<th>GEOMETRY</th>
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<tr>
<td></td>
<td>XX</td>
<td>X</td>
<td>XXX</td>
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<td>MOLDING</td>
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**Forming Technologies - Prepreg Compression Molding: a novel mass production approach through dedicated preformers**

Also prepreg technology is being revolutionized in a mass production perspective. New generation, fast curing prepregs are becoming available for compression molding. The suppliers of these kinds of materials have achieved outstanding results in the reduction of curing times. Prepregs for compression molding now, therefore, represents a good compromise between curing time, surface quality and achievable fiber volume fractions [3].

Fast compression molding of these types of prepregs, however, would not be possible without preforming. Preforming, in fact, enables a fast loading into the mold of the material that, otherwise, would cure in the hot cavity while being positioned. The manual lamination of the prepreg is a long operation that needs time due to the necessity of draping the stack of prepreg layers into the mold. Dedicated and innovative preforming machines have, therefore, been developed.

The machine can implement a stacking phase followed by a first heating preceding the preforming. During the first heating stage, the material is brought to an intermediate temperature (lower than 80°C) in order to reduce the viscosity of the material and allow a good drapability. Since curing kicks off at temperatures higher than 80°C, this will not engage the chemical reaction. As a next step, into the preforming mold, the temperature is brought down again in order to “freeze” the pre-shape.

As for dry fabrics, the automatic transfer and draping of the material represents a technical challenge that is overcome through dedicated intelligent gripping systems having multiple independent gripping hands capable of applying a controlled local tension to the material.

**Figure 17**: Prepreg Multi Station Preformer

**Figure 18**: Prepreg Preformer
Figures 17 and 18 show the concept behind the first mass production performer for prepreg ever produced and that have been delivered in June 16. After the material has been preformed, it can be molded at high temperatures (150ºC is a typical value) through a dedicated molding press. Prepreg opens the way to the adoption of local reinforcements also in composites mass production. The absence of a viscous liquid resin flowing through the preform (as in HP-RTM) allows the local reinforcement to maintain its position in a stable way.

From the equipment manufacturer perspective, this has two consequences. Preformers must allow to deal with local reinforcements allowing the operator or the robot to ergonomically place and assemble additional patches into the preforming mold. On the press side, being prepreg molds equipped with shear edges (upper mold abuts directly on the material surface) advanced parallelism control systems are a must in order to compensate the asymmetric counter forces that the material can apply to the mold while it is being closed. These counter forces can result in torques that destabilize the planarity of the mold during its downward stroke.

Parallelism control uses four linear transducers with a resolution of 0.005mm to detect the deviation of the platen from the plane and actuates the servo-valves that control the hydraulic pistons so that the deviation is compensated.

**Forming Technologies - Carbon Fiber SMC**

In order to cope with the need of mass producing CFRP structural automotive components, a carbon fiber based version of SMC has been made available by the chemical industry.

This material maintains the relative simplicity of SMC molding exploiting the improved mechanical properties of carbon fibers when compared to glass. The matrix is a vinyl ester based. Curing times can range from one to three minutes and are achieved with mold temperatures that can range from 145ºC to 160ºC. [4]

From the equipment side, the technology consolidated in GF-SMC can be leveraged to achieve dedicated CF-SMC molding lines. Presses, also in this case, need to be equipped with parallelism control to cope with torques that can be transferred by the material to the platen in the flowing and molding stage.
Dedicated handling systems have been developed to automatize the process. Loading of the raw material is performed through needle grippers while unloading is performed through vacuum grippers.

CF-SMC and its flowing properties can be effectively used to over-mold local reinforcements over already cured parts. Through this strategy, ribs can be created to increase the stiffness of the final part in an automated and fast way.

![Diagram of CF-SMC process](image)

**Figure 21: CF-SMC as local reinforcement**

One of the biggest challenges that chemical companies are currently facing is in developing CF-SMC materials to improve the flowability of the material, especially when high fiber volume fractions are in place. As of today, high fiber volume fractions (in the order of 50 to 60%) can imply in mold pressures ranging around 80 bars. Presses, therefore, need to have high clamping forces.

**Conclusions**

The paper has shown how composites molding equipment manufacturers are constantly developing solutions to support the industry in facing the challenges of mass production. In parallel, the chemical industry is making huge steps ahead towards the reduction of curing times opening the way to a deeper penetration of composites in large scale automotive. The clear conclusion is that a remarkably diverse set of technologies and tools is being developed to answer to the specific requirements of each part. As an outlook on the future, our strong belief is that tomorrow’s CFRP chassis will make full use of that diversity to exploit at best the tunable properties of CFRP.

**Acknowledgments**

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