FAST-CYCLE CFRP MANUFACTURING TECHNOLOGIES FOR AUTOMOBILE APPLICATIONS

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Abstract

Fuel consumption and CO_2 emission reductions have been driving automobile industries toward the use of carbon fiber composite materials for metal replacement, part integration and part consolidation. To satisfy high demands of automobile makers, especially for low to mid-end automobiles, where a high production rate as well as moldability-performance trade-off of composite parts are seriously considered, Toray has introduced innovative fast-cycle manufacturing technologies for both fabric and unidirectional carbon fiber composites. The former is achieved with a novel resin system for 10-min cycle time in an isothermal resin transfer molding in that resin impregnation and curing take 3 min and 5 min, respectively, while mold setting and demold take 1 min each. The latter, on the other hand, is achieved by slitting continuous fibers of a fast cure unidirectional prepreg at a desired angle from the fiber's axis at a certain interval to increase drape-ability while maintaining their original positions in the prepreg. In addition, Toray's reinforced interphase technology could be fine-tuned to further reduce the performance gap between the slit and the unslit prepregs.

The present paper will discuss model CFRP systems in terms of fast cycle time, moldability and mechanical properties.

Introduction

Desired performances of a CFRP part often dictate its manufacturability optimized for both moldability and total cycle time, which is translated directly to part quality and process cost, respectively. While a prepreg of unidirectional continuous fibers impregnated by a resin offers the highest performances compared to resin transfer molding (RTM) for continuous fiber fabrics and compression molding for short fibers, its manufacturability is by far the poorest and vice versa. High performances from the prepreg are resulted because it allows ply thickness and fiber area weight to be controlled and fibers to be aligned in a load direction as desired, while poor manufacturability comes from poor moldability as a stack of cut prepregs could not effectively conform onto a mold's surface. Moldability could be improved if a RTM process is used in that the continuous fibers are made into a dry fabric and laid up to be conformed to the mold's surface (viz., preform), and the resin is infused into this bed of fibers. However, the resulting part could suffer a performance penalty due to an insufficient arrangement of fibers to accommodate a load and resin-rich areas. Further improvement on moldability can be achieved with a mixture of short fibers and the resin in a compression molding process. Nevertheless, this approach greatly reduces performances due to short fiber lengths and a poor fiber distribution. Of the three manufacturing methods, RTM is the most suitable for automobile applications where a high production rate, part quality and high performance are sought.

With the high demands of automobile makers for low-cost CFRP parts, especially for low to mid-end automobiles, while cost of raw materials including resin components and carbon fibers could be reduced to a certain extent, the majority cost reduction is pushed by shortening a manufacturing cycle as much as possible. Certainly, a quick-cure resin system suitable for a straight ramp or a constant cure temperature is desired to achieve the shortest possible cure time. However, since flowability and cure rate tend to go in opposite directions, the resin has to be optimized to have a certain flow time to wet out all dry spots before it is set, i.e., an optimized cure profile is sought. Additional time saving could be achieved by eliminating unnecessary steps or combining steps in a mold setting process. This varies depending on the desired forms of carbon fibers either unidirectional, fabric, or short fibers in the cured part in that unidirectional prepreg and RTM could take a substantially long time, proportional to the size and geometry of the part. Finally in some cases a demolding process could be shortened if it could be integrated with the mold setting and curing processes.

The present paper will discuss Toray's recently developed manufacturing technologies to overcome long cycle time for both fabric and unidirectional fibers, suitable for automobile applications. Model material systems are used to demonstrate the concepts.

Materials and Methods Discussion

1. Fast-Cycle RTM for Carbon Fiber Fabrics.

Popular processing approach for fabrics is RTM as shown in Fig. 1. Relatively low tooling and equipment costs attract automobile makers to seek this method. To make this process even more cost effective, Toray has introduced a rapid flow-to-cure resin system that has a relatively low viscosity at a cure temperature, allowing it to flow and impregnate a dry fiber bed for a period of time and instantaneously cured after this period of time has passed [1]. The temperature can be fine-tuned for a part's geometry and size so that flowability and curability are optimized to achieve a high part quality.

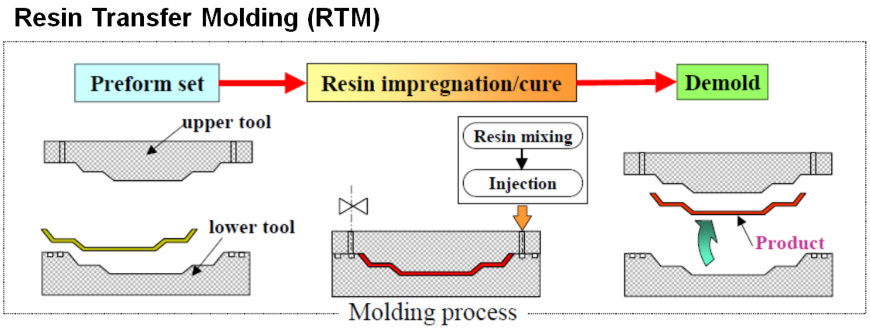

Fig.1 – Typical conventional resin transfer molding process for fiber fabrics.

Three epoxy resin systems as follows were selected in this study:

- TR-C32: Toray's standard amine cured epoxy resin system for producing CFRP automobile outer panels by a RTM process, used as a control
- HS1: An anionic polymerized epoxy resin, a mixture of liquid bisphenol A type epoxy resin and 2-methylimidazole (3 parts per 100 parts of epoxy or 3phr), used as an comparative example to the HS2 resin
- HS2: An anionic polymerized epoxy resin with a chain transfer agent, a mixture of liquid bisphenol A type epoxy resin, 2-methylimidazole (3 phr) and an alcoholic type chain transfer agent (3 phr), used to demonstrate the resin concept

After injected into a fiber bed of 9 plies plain weave Torayca T300-3K fabric with a fiber area weight of 190 g/m^2, each resin was cured at a constant temperature of 100 ^{0}C. Compared to TR-C32, a longer time for the concept HS2 resin to reach 10 % cure index (viz., flowability) and a shorter time for it to achieve 90 % cure index (viz., curability), i.e., better flowability and curability (Fig. 2) were observed. Even having a small amount of 2-methylimidazole, it was enough to facilitate the quick curing process until completion as shown by the HS1 resin. When added the chain transfer agent to the HS1 resin, some of the epoxy chain growths were shortened while others continued growing. This promoted a longer flow time for a short period of time until the short chains started combining to form the final network, which leads to a rapid reaction rate. Flowability and curability could be optimized for a specific application by controlling the cure temperature (Fig. 2). It seems that 105^{0}C was the optimal cure temperature for the HS2 resin.

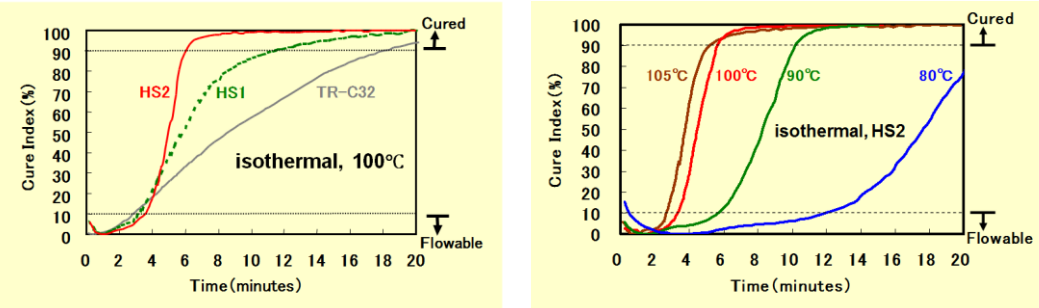

Fig.2 – Flowabilty vs. curability of the concept resin HS2 compared to typical RTM resins. Flowability and curability is defined as a time it takes the resin to reach 10 % and 90 % cure index, respectively. A longer time to reach 10 % means better flowability while a shorter time to reach 90 % means better curability.

To promote a better and quicker impregnation, Toray also employed a rapid impregnation process (Fig. 3) in which the pressurized resin was quickly introduced on top of the dry fiber bed and gradually pulled into the fibers through thickness by a vacuum source [2]. For a panel size of 700 mm x 350 mm x 2 mm, a total cycle of 10 min was achieved in that resin impregnation and curing at 105 ^{0}C took 3 min and 5 min, respectively, while mold setting and demold took 1 min each. The cured panel was examined to have no void and resin-rich areas. Mechanical properties were comparable to the commercialized TR-C32 system, shown in Tables I-II.

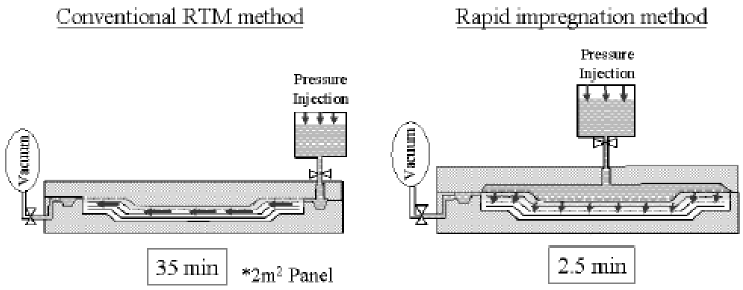

Fig.3 – Comparison between conventional and rapid resin impregnation process.

Table I – Mechanical properties of cured resin

		TR-C32	HS2
Tensile modulus	GPa	3.3	3.8
Tensile strength	MPa	84	79
Fracture tensile strain	%	5.7	4.1

*Table II – Properties of CFRPs (*normalized to V_f = 60 %)*

		TR-C32	HS2
0°tensile modulus*	GPa	68	68
0°tensile strength*	MPa	680	650
0°compression strength*	MPa	610	620
T_g	℃	108	116

2. Fast-Cycle Highly-Moldable Prepregs

Prepregs of unidirectional fibers are commonly used in aerospace applications where high strength and facture toughness are sought. The prepregs can be made with a variety of fiber areal weight and resin amount, allowing a flexibility in lay-up to maximize the potential of the fiber composite. However, because bending stiffness of the prepreg is greatly higher than dry fabrics, it is very challenging to conform the prepreg onto a mold surface, especially for a part with curvatures, sharp corners and deep-drawing features. To address this shortcoming, the bending stiffness should be reduced. Toray's method is to slit continuous fibers of the prepreg at a desired angle from the fiber's axis at a certain interval so that these cut fibers maintain their original position [3] (Fig. 4). This approach maintains the integrity of the prepreg but increases its drape-ability and allows the control of fiber orientation and resin content offered by the unslit prepreg. The slitting method can be applied to any prepreg regardless of fiber area weights and resin types. The slit prepreg is called *unidirectionally arrayed chopped strands* (UACS). Generally, the slitting angle was found to be less than 25^0 to maintain a good molded surface quality (Fig. 5) as well as at least 75 % of quasi-isotropic laminate strength of the unslit prepreg (Fig. 6). The resulting slit prepreg is called enhanced UACS. Further improvement in strength of enhanced UACS prepregs could be achieved with the recently developed interphase technology by Toray, who engineered layers of nanomaterials localized in the interfacial region between the fiber and the cured resin, and this allowed up to 100 % strength translation of carbon fiber to the corresponding fiber composite (Fig. 7) [4]. This study is currently under investigation at Toray Composites (America), Inc.

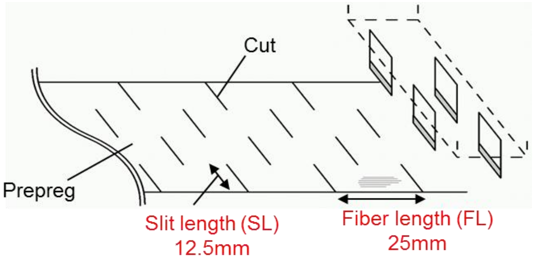

Fig. 4 – Slitting method for an unidirectional prepreg for drape-ability improvement.

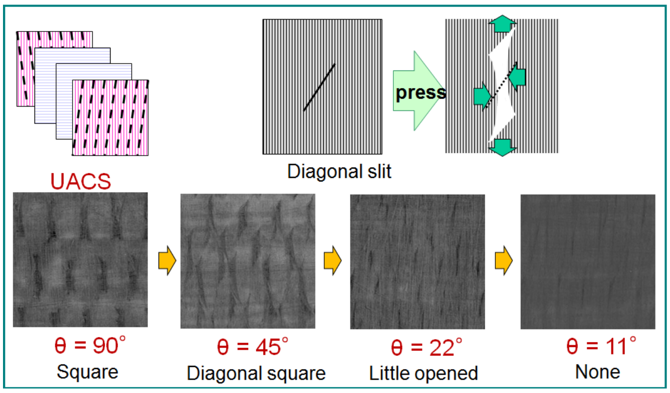

Fig. 5 – Surface quality versus slitting angle. Lower angles give a better surface finish.

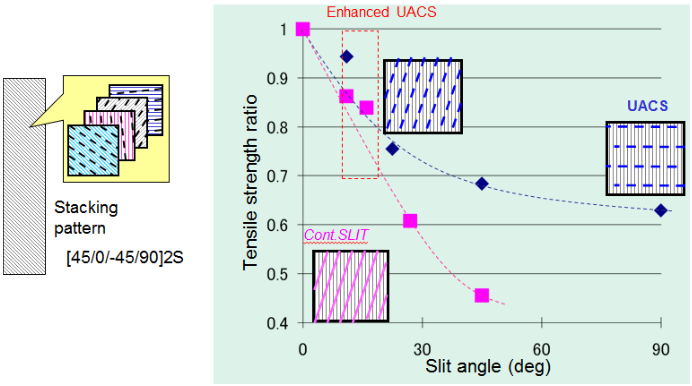

Fig. 6 – Relative strength versus slitting angle. Quasi-isotropic lay-up was used. Enhanced UACS prepreg from a slitting angle of less than 25^0 retained at least 75 % strength of the unslit prepreg

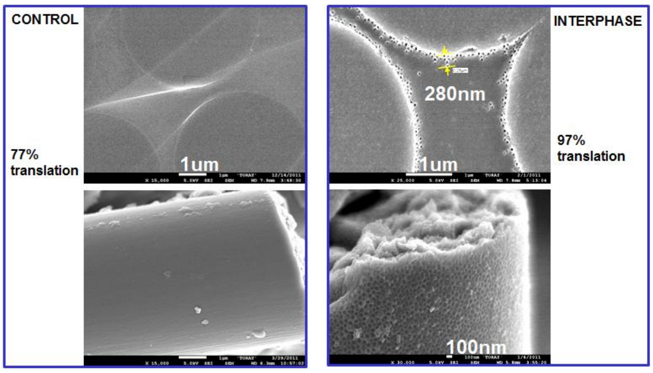

Fig. 7 – Toray's reinforced interphase technology with nanomaterials for CFRPs. Percent translation defines as the ratio of measured tensile strength of the CFRP and the product of strand strength of carbon fiber and fiber volume fraction in the CFRP. 100 % means carbon fiber strength is realized completely in the CFRP. Without the reinforced interphase, typical range of translation is 60-85 %.

Molding test of enhanced UACS prepregs were successful at 135-145 ^{0}C from 5-10 min in a compression mold for a variety of parts with sharp corners, rib structures and deep-drawing (50 mm tall) features (Fig. 7). The surface finish was excellent. Cross sections of these parts showed good fiber distribution compared to a part molded from unslit prepreg.

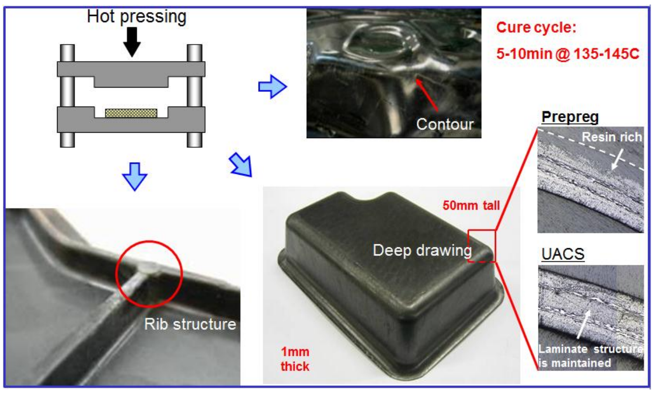

Fig. 6 – Examples of compression molded part with UACS prepregs. Resin-rich areas typically found in a part molded with unslit prepreg were resolved effectively.

Conclusions

In response to high demands of automobile makers for the production of low cost CFFRP parts for low to mid-end automobile, Toray has introduced fast-cycle manufacturing technologies for both fabrics and unidirectional fibers for high performances and surface quality of a molded part. The rapid cure resin technology combined with a RTM process for fabrics has achieved a 10-min cycle time. The slitting technology when combined with the rapid cure resin technology and the interphase technology could offer an alternative choice for automobile makers to process unidirectional fibers in applications where the use of fabrics might be a constraint. These manufacturing technologies could address challenging automobile applications where a high production rate, part quality and high performance are sought.

References

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