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Fabrication of carbon fiber SMC composites with vinyl ester resin and effect of carbon fiber content on mechanical properties

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Fiber reinforced composites are being used in the automotive industry and other manufacturing fields. Their properties, including high specific stiffness, strength and weight reduction make fiber composite materials an attractive replacement for metal components. The development of composites like carbon fiber reinforced plastic and related production technologies have contributed to the increasing application of fiber composite materials. Many new components have recently been adapted, including structural parts such as roof frames, under floors, trunk hoods and so on, using sheet molding compound (SMC) and resin transfer molding processes [1-5].

SMC is the most successful application of fiber reinforced composites in the automotive industry. SMC consists of resin, reinforcement fibers, filler and various additives. In the case of fiber reinforced plastic composites, the resin functions to hold the fibers together like glue, transferring stress between the reinforcing fibers, and protecting the fibers from mechanical and environmental damage. An important function of the reinforcing fiber is to carry the load along the length of the fiber. The mechanical properties of SMCs with random fiber distribution can be increased by using carbon fibers as reinforcement instead of glass fibers [5-9]. To date, most studies have focused on the use of glass fiber, and the data for the analyzed results show various opinions and various tendencies. Al-Maamori et al. [10] reported an increase in shear modulus when the glass fiber content was increased from 5 wt% to 25 wt%. Lee et al. [11] showed that the tensile modulus and flexural modulus increased with increasing fiber content from 10 vol% to 30 vol%.

On the other hand, the tensile strength showed a maximum value at a fiber content of 20 vol% and a flexural strength at a fiber content of 15 vol% [11]. Palmer et al. [7] reported an attempt to develop a new SMC using low cost recycled carbon fiber as the reinforcing components in place of conventional glass fibers. The AOC company in the US announced ultra-low density SMC (1.05 g/cm^3) with a 31% glass-filled Atryl polyester resin, which offered tight tolerances, heat resistance, and molded-in features for truck sunshades [12].

In this paper, SMC materials were fabricated using vinyl ester resin and chopped carbon fiber based on 1-inch lengths. The vinyl ester resin has the advantages of high curing speed and high productivity. The carbon fiber contents were 40, 45, 50 and 55 wt%, which is higher than the general carbon fiber SMC content of 25–35 wt%. The mechanical properties of the carbon fiber SMC fabricated under the above conditions were then evaluated. Tensile tests and flexural tests were carried out and the fracture surface was observed using a normal scanning electron microscope (SEM) (AIS200c; Seron Technologies Inc., Korea). Mechanical tests were performed using a Shimadzu universal testing machine, with a max force of 100 kN (AG-X plus; Shimadzu Corp., Japan). Testing conditions were performed under standard climate conditions and referenced according to the American Society for Testing and Materials (ASTM) D638 and ASTM D790 Standard test methods.

Fig. 1a shows the manufacturing process for continuous in-line compound SMC. The paste is spread uniformly onto the bottom film. Chopped carbon fibers are randomly deposited onto the paste. The top film is introduced and the sandwich is rolled into a pre-determined thickness. For the chopper, 48 spiral grooves and a scissors structure were applied. The

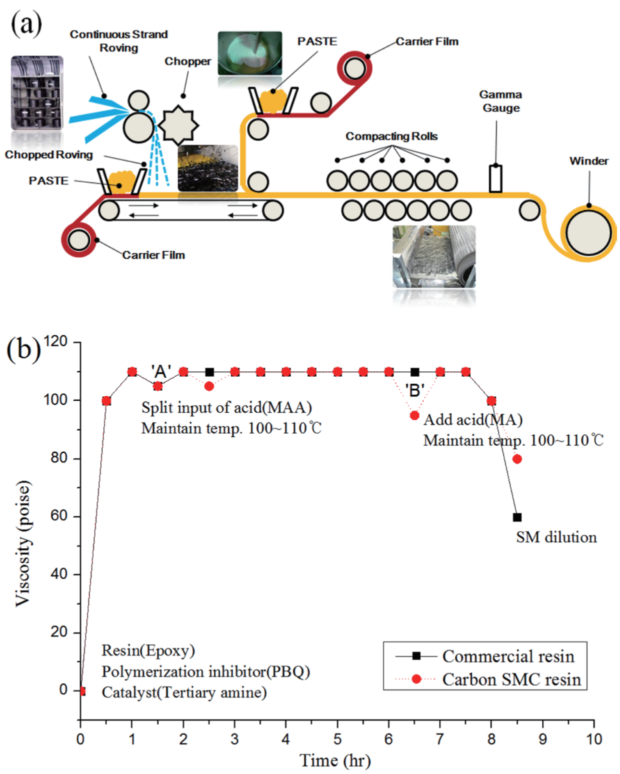

Fig. 1. (a) Schematic illustration of the sheet molding compound (SMC) manufacturing process [6], (b) design of the vinyl ester resin for the carbon SMC. MMA, methyl methacrylate; MA, maleic anhydride; SM, ---; PBQ, ---.

sheets were stored for one week and then formed by pressure and heat using a hot press at a temperature of 150°C, a pressure of 10 MPa, and a curing time of 5 min [6].

Fig 1b shows the design process of the vinyl ester resin for the carbon SMC. In a commercial resin, methyl methacrylate is mixed with the epoxy resin at point 'A,' but this makes it difficult to thicken. For this reason, maleic anhydride was added at point 'B' to make the resin for the carbon SMC.

The SMC compound's materials include these ingredients: the thermoset matrix resin (vinyl ester based resin), additives such as catalysts (tertiary amine) and thickeners (MgO), a low shrinkage agent (LPS-40PS), polymerization inhibitor (PBQ [ST-S]), mould release agent (Zinc-St), fillers ($CaCO_3$) and reinforcements (1 inch chopped carbon fiber). For the reinforced carbon fiber, Mitsubishi Rayon 12K (Japan) fiber was used, and the fiber content was set to 40, 45, 50 and 55 wt%.

The composition ratios of bisphenol A type epoxy resin, acrylic monomer and styrene monomer were used for the resin design. Table 1 shows detailed information on the composition of the resin system.

Carbon SMC sheet was prepared using the recipe in Table 1 and the average molecular weight and viscosity data in Fig. 2. In Fig. 2a shows the gel permeation chromatography (Hewlett-Packard, Breeze 2) of the behavior of the developed resin. M_n is the number average molecular weight, M_w is the weight average molecular weight and M_z is the volume average molecular weight. M_w/M_n refers to the degree of dispersion (polydispersity), and the larger the M_w/M_n, the broader the molecular weight

Table 1. Materials for preparation of the vinyl ester resin system

Materials	Contents (wt%)
Epoxy	33.5
HQ-S (quinone)	0.022
Methyl methacrylate	15.6
Tertiary amine	0.092
Styrene monomer	41.9
Stabilizer	0.023
Maleic anhydride	8.9

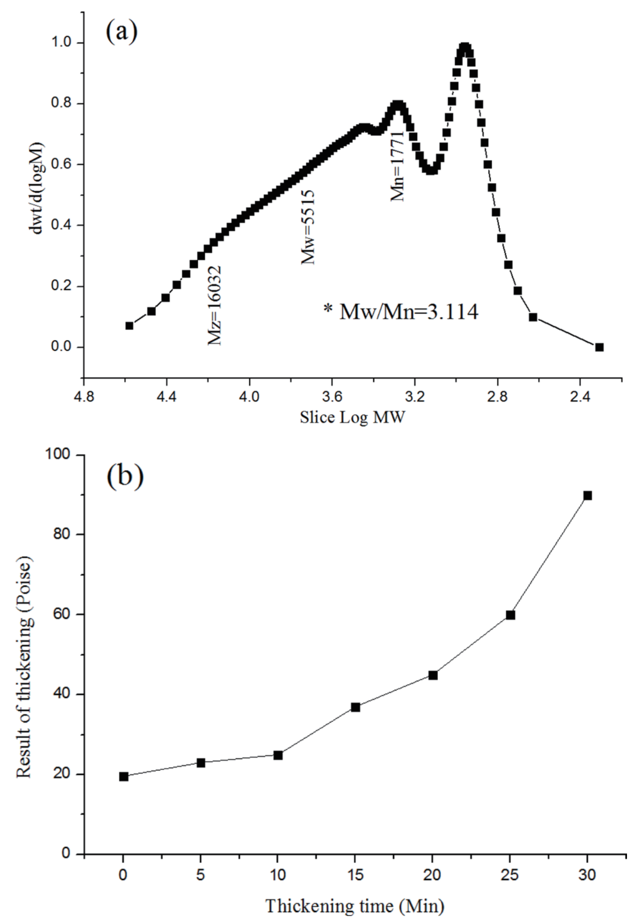

Fig. 2. (a) Broad unknown relative chromatogram of development resin, (b) viscosity characteristics of the developed carbon sheet molding compound resin. M_n, number average molecular weight; M_w, weight average molecular weight; M_z, volume average molecular weight; MW, molecular weight.

distribution (MWD) of the polymer. The M_z value is 16,032, the M_w value is 5,515, the M_n value is 1,771 (daltons) and the MWD value is 3.114.

The molecular weight of the resin for SMC is related to the thickening behavior of the SMC sheet. In the case of a general vinyl ester resin, it should have a weight average molecular weight of at least 2000 to 3000, but for SMC, it should have a

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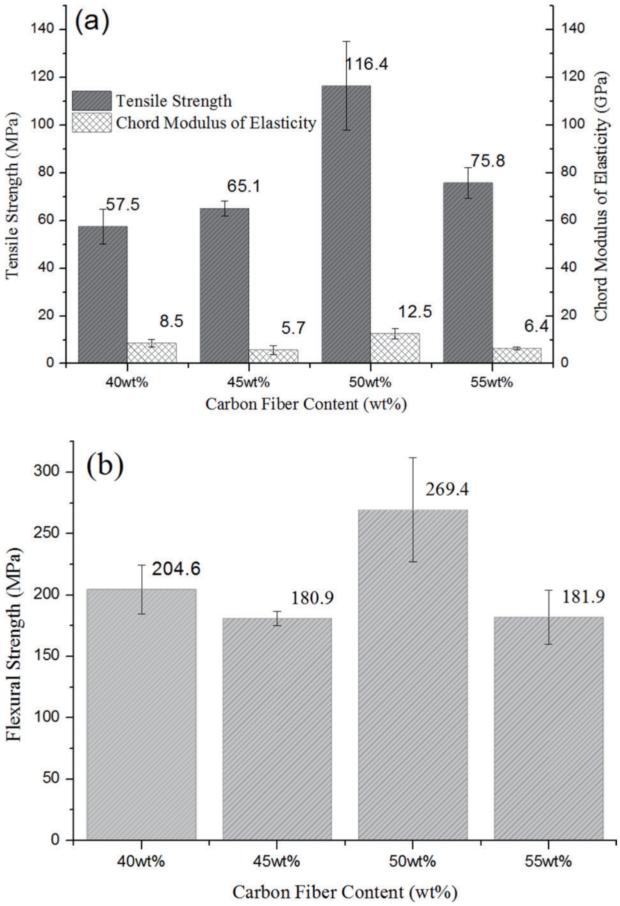

Fig. 3. Mechanical test results of the carbon sheet molding compound for (a) tensile test and (b) flexure test.

weight average molecular weight of 4000 to 5000. In this case, the SMC sheet can be compressed and formed.

Fig. 2b presents the viscosity characteristics of the developed SMC resin. The viscosity was measured using a viscometer (DV1 Viscometer; Brookfield, USA) and a constant temperature bath (JSWB-11T, JS Research Inc., Korea). For the developed SMC resin, the initial slope is low until 10 min, and after 10 min, the slope rapidly increases, as can be confirmed. The viscosity increased by about 5 times within 30 min. If the viscosity does not increase by more than 4 times in 30 min, the final viscosity of the SMC sheet will not reach a viscosity suitable for forming. For the above reasons, the vinyl ester resin synthesized in this study appeared to be suitable for SMC.

Tensile tests and flexural tests were carried out on SMC sheets produced by hot press in accordance with ASTM D638 and ASTM D790 standards [13,14]. Fig. 3. shows the results of the tensile and flexural tests. As the fiber content increases, the tensile strength, tensile elastic modulus and flexural strength tend to increase relatively. This tendency is observed until the fiber content reaches 50 wt%, and when it exceeds this, the mechanical property is decreased due to the impregnability problem.

Fig. 4 shows the SEM image of the fracture surface after the tensile test. Compared with a conventional SMC having a

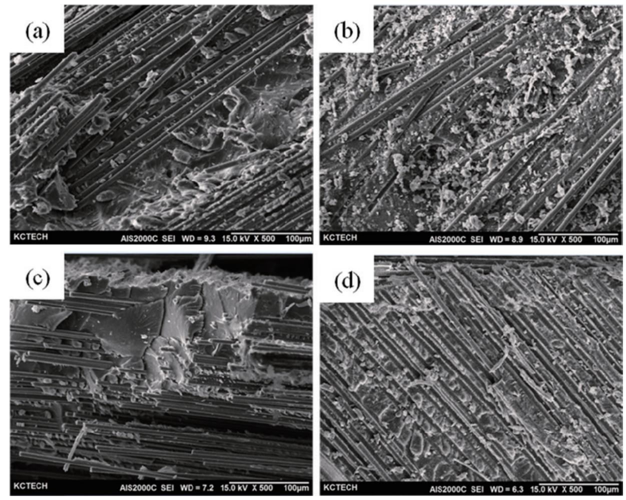

Fig. 4. Scanning electron microscope images of carbon fiber sheet molding compound with fiber contents of (a) 40 wt%, (b) 45 wt%, (c) 50 wt%, and (d) 55 wt%.

fiber content of 25 to 35 wt%, the resin impregnation rate as a whole is lower due to the high fiber volume content of the carbon SMC produced in this study. When the fiber content is from 40 to 50 wt%, the fibers are cut off in the middle, but when the fiber content is 55 wt%, the fibers are generally peeled off from the resin.

In this paper, a carbon SMC composite with vinyl ester resin compound was prepared. The molecular weight and the thickening behavior of the prepared vinyl ester resin were analyzed to confirm that it was suitable for the carbon SMC resin. The molecular weight of the resin for SMC is related to the thickening behavior of the SMC sheet. The weight average molecular weight of the synthesized SMC vinyl ester resin was 5515. Within 30 min, the initial viscosity of the SMC resin increased about 5 times. This value of molecular weight and initial thickening behavior is suitable for compression molding of the SMC sheet. The effect of the carbon fiber content from 40 wt% to 55 wt% on the mechanical properties of the carbon SMC composite prepared with the proven vinyl ester resin was investigated by measuring the mechanical properties, and by SEM image analysis. The tensile and flexural characteristics of the carbon SMC composite were increased up to 50 wt%, although the impregnation was insufficient compared to the conventional SMC composite.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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