PREDICTION OF ENERGY INTENSITY OF CARBON FIBER REINFORCED PLASTICS FOR MASS-PRODUCED PASSENGER CARS

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ABSTRACT

Carbon fiber reinforced plastics (CFRP) have recently attracted much attention as light materials in the automotive industry, in particular in mass-produced passenger cars. However, the large energy consumption, the difficulty of the recycling process, and the high cost have inhibited its widespread use in general industrial field. So, we have to decrease the energy intensity of production to the level of steel and reduce the initial cost in order to use CFRP for mass-produced passenger cars. Up to now, CFRP that we have discussed has been for aircrafts, so it has been very advanced and its energy intensity has been much larger than that of steel. So, in this study, we calculated energy intensity of CFRP whose specification was for mass-produced cars by use of energy intensity of carbon fiber (CF) that was newly calculated some years ago. After calculating, it was still much larger than that of steel when only virgin CF was used, though it decreased dramatically when we rightly chose fiber fraction and a kind of matrix resin. 3R (reduce, reuse, and recycle) technology, thus, was very important. We found that the effective combination of the 3R could decrease the energy intensity of CFRP to the level of steel parts.

KEYWORD: CFRP, car, energy intensity

1. INTRODUCTION

Progress of fuel efficiency is strongly needed to reduce environmental burdens in the transport sector. Lightening vehicles is a very important technology that can contribute to easing the burden. In recent years, many engineers have thought about switching from conventional steel to light metals such as aluminum, and even to advanced composite materials. In particular, carbon fiber reinforced plastics (CFRP) have such high specific strength and specific rigidity that they are widely used in the fields of aircraft, space, military, and other high-tech fields. CFRP, however, has not come into practical use for the automotive industry because of the large energy consumption, the difficulty of the recycling process, and the high cost.

84 % of life-cycle environmental burdens of a passenger car are produced in the use stage [1], so light materials, which progress fuel efficiency, are generally very useful. Moreover maintenance costs go down because the amount of fuel use. However initial cost is very important, which means we need to reduce the costs other than use to the level of conventional steel vehicles, in order to further promote the use of CFRPs in the mass-produced car market. Using CFRP for mass-produced cars needs energy intensity to be about the value of steel because costs of basic materials are generally in proportion to the energy consumption of production.

In this paper, we demonstrated conditions of using CFRP not for aircrafts, which need very high performance, but for mass-produced passenger cars, and proposed a direction of research and development.

2. ENERGY INTENSITY OF CFRP MADE OUT OF VIRGIN MATERIALS

2.1 Target value of energy intensity of CFRP parts First we talk about energy intensity of steel parts. Almost all of the steel for vehicles is virgin because it needs high performance, so its energy intensity is a little higher than that of steel for general structure, which means 33 MJ/kg [2]. And energy consumption of its process and assembly is 16 MJ/kg [1]. So, energy intensity of steel parts is 49 MJ/kg, which means we should set energy consumption of CFRP parts to be about 50-55 MJ/kg as a target.

2.2 Energy intensity of production of CFRP parts by using virgin material

2.2.1 Energy intensity of production of carbon fiber (CF) One of the reasons for the very large energy intensity of CFRP is that of the energy intensity of carbon fiber (CF), which is a main material, is very large. Energy intensity of PAN-based CF calculated in 1999 [3] and that in 2004 [4] are shown in Table 1. Energy consumption of processing and assembling the product is much larger than that of raw material production. After the recalculation, the former value is still very large, though it decreases by about half, and it would decrease continuously. The reason is that operation rates of the current CF production lines are low because various types and quality of CF are made in the line, and that there are many inefficient processes because the production scale is small. In other words, CFRP's history is much shorter than that of steel and it has a lot of room for technological development. The energy intensity, thus, would be lower and lower if CFRP is produced in large quantities, which CFRP is limited to the application to mass-produced cars and the production is rationalized.

2.2.2 Energy intensity of production of matrix resins Epoxy is commonly used as a matrix resin of thermosetting resin for aircrafts and other high-tech products. As shown in Table 2, energy intensity of epoxy is relatively larger, so energy intensity of matrix resin could decrease when it is changed to another resin. Selection of matrix resin, however, has a great impact on performance of composite materials. Thermosetting resin is superior in terms of specific strength, specific rigidity, and durability, while thermoplastic is superior in terms of cost and 3R (reduce, reuse, and recycle). Mechanical properties that parts require, thus, are more important than the size of the value of energy intensity in terms of the matrix resin.

2.2.3 Decrease of energy intensity by removing of prepreg production Prepreg is an in-process material to stabilize molding quality and simplify handling. Energy consumption of the prepreg

Table1 Energy intensity of steel and CF

	Steel (MJ/kg)	CF (MJ/kg)	
		In 1999	In 2004
Raw material production	-	42	39
Processing and assembly	-	436	247
Total	33	478	286

Table2 Energy intensity of matrix resins

	Energy intensity (MJ/kg)
Epoxy	76.0
Unsaturated polyester	62.8
Phenol	32.9
Flexible polyurethane	67.3
High-density polyethylene	20.3
Polypropylene	24.4

Table3 Energy intensity of prepreg production

Production process	Energy intensity (MJ/kg)
Resin blending	0.1
Resin coating	1.4
Resin impregnation	2.1
Prepreg winding	0.2
Atmosphere control	20.8
Raw material storage	11.5
Prepreg storage	3.4
Release coated paper production	0.5
Total	40.0

Table4 Energy intensity of molding

Molding method	Energy intensity (MJ/kg)
Hand lay up	19.2
Spray up	14.9
RTM	12.8
VARI	10.2
Cold press	11.8
Preform matched die	10.1
SMC	3.5
Filament winding	2.7
Pultrusion	3.1

production and storage would dramatically decrease when production lines from CF to CRRP parts are made on the premise of mass production.

A breakdown of energy consumption of prepreg production process, which is CF-unidirectional by the dry system method, is shown in Table 3. Almost all of the energy consumption is produced from atmosphere control and storage of raw materials and products. These processes are needed to prevent expansion and contraction by temperature change and adhesion of foreign substances such as dust. The energy consumption, however, would be about zero in the case of mass production because the processes are not needed. And it would be one-tenth even if prepreg is needed because atmosphere control and storage are also not needed.

2.2.4 Energy intensity of molding CFRP for aircrafts are mostly made by autoclave molding and the energy consumption is so large that there is data that it is more than 600 MJ/kg. Additionally, the molding speed is very slow. So we think that resin transfer molding (RTM) method and preform matched die method are good for CFRP molding for mass-produced cars. As shown in Table 4, energy intensity of these processes is 10-13 MJ/kg. Moreover, we believe that the sheet molding compound (SMC) method and the injection molding method in the future will further decrease energy intensity by a few MJ/kg.

2.2.5 Energy intensity of CFRP for body As shown in Figure 1, thermoplastic CFRPs (CFRTP) are suitable for the automotive body because it requires a high value of rigidity. The larger fiber volume fraction is better when you think that performance is more important, while the lower is better when you think that cost and environmental burdens are more important. We thought that fiber volume fraction would be 30-50 % because board thickness increases and specific strength becomes worse when fiber volume fraction is low. In this paper, the fiber volume fraction was 30%, the matrix was polypropylene (PP), and the molding method is preform matched die. Energy intensity of carbon fiber (CF) and PP is 286 MJ/kg and 24 MJ/kg respectively. Weight ratio between CF and PP was 0.462 : 0.538, so energy consumption of CF and PP was 132 MJ/kg and 13 MJ/kg respectively. Energy intensity of the molding is 10 MJ/kg. Therefore the energy intensity of the CFRP was 155 MJ/kg (Fig.3).

2.2.6 Energy intensity of CFRP for chassis As shown in Figure 1, CFRP, whose fiber volume fraction is large, in particular thermosetting CFRP (CFRTS), have high weight reduction potential in

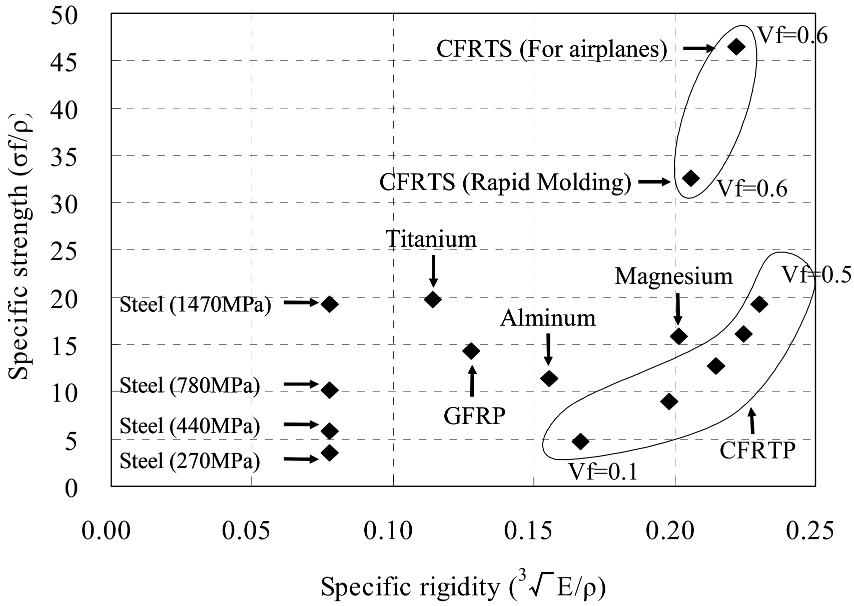

Fig.1 Specific rigidity and specific strength of various materials

the case of chassis, which puts importance on strength. Energy intensity of epoxy (EP) is 76 MJ/kg. Weight ratio between CF and EP was 0.692 : 0.308, so energy consumption of CF and EP was 198 MJ/kg and 23 MJ/kg respectively. Molding method is resin transfer molding (RTM), and its energy intensity is 13 MJ/kg. Therefore the energy intensity of the CFRP was 234 MJ/kg (Fig.3).

2.2.7 Energy intensity of process and assembly Energy consumption of process and assembly would be very small because the final shape is almost incorporated during the making of the material. Additionally CFRP will benefit in terms of cost and molding speed because integral molding dramatically decreases the number of parts.

3. ENERGY INTENSITY AFTER 3R

3.1 Decrease of energy intensity by 3R In the former chapter, we analyzed inventory of CFRP made out of virgin materials on the premise of using for mass-produced cars. Environmental burdens of production were still much larger than that of steel. So 3R (reduce, reuse, and recycle) is essential in order to improve competitiveness of the products in terms of cost and environmental burdens. 3R of CFRP, however, have hardly been done because the small amount of CFRP wastes. We, thus, need to further research and develop required technology by using inventory analysis in order to optimize the 3R system.

3.2 Scenario of 3R Prediction of reuse and recycle flow of scrapped CFRP cars is shown in Figure 2. Currently the technological development is promoted in two main approaches.

One is applying technology of current thermosetting CFRP (CFRTS). It has a very high-performance and durability. In particular, it has a good advantage in resistance against rust, which has a great influence on the lifetime of cars. However, separating CF from CFRTS is very difficult and additional supply of virgin resin is essential in remolding. Thus we use CFRTS for as long time as possible by reuse when the composite material goes below and acceptable value we can separate the fiber and add virgin matrix resin to start fresh again. This represents a cascading recycle process.

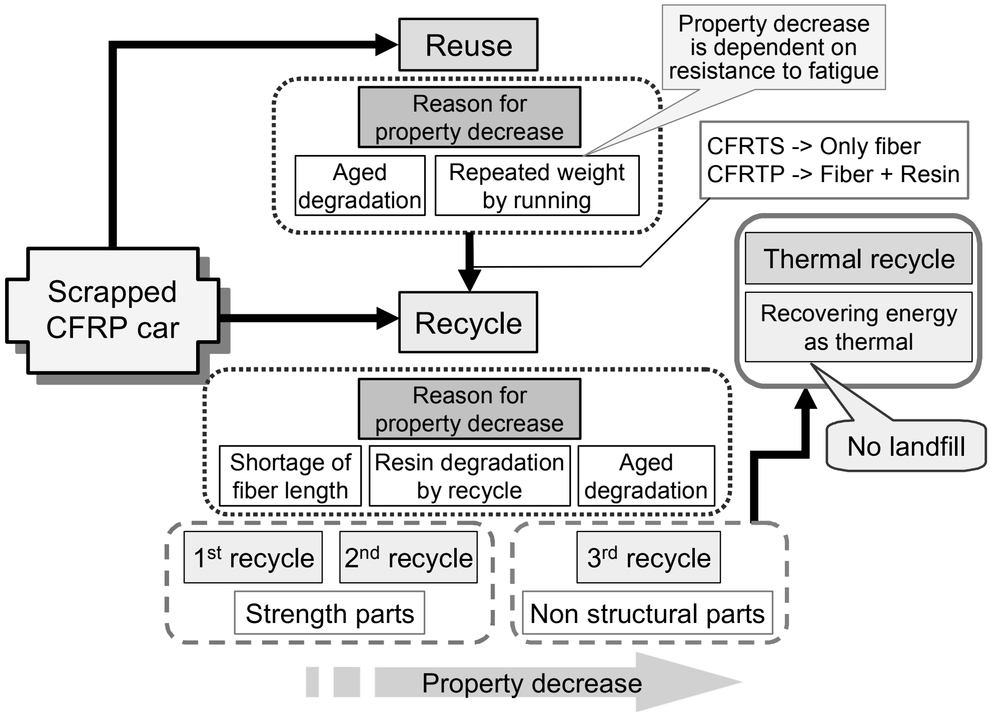

Fig.2 Reuse and recycle flow of scrapped CFRP cars in the future

The other is the practical application of thermoplastic CFRP (CFRTP), which is more ideal than CFRTS. CFRTP is cheaper and allows a very efficient process, repair, and remolding by heat. However, adhesion of CF to thermoplastic resin is currently very poor. Moreover, fiber length shortens in recycling and it needs additional virgin CF.

Naturally, the performance is worse and worse after repeated such recycling. So technology of sandwich materials, which means recycled CFRTP reinforced by adhering sheets having long fiber on both sides, is studied.

3.3 Estimate of energy intensity of CFRP for mass-produced cars

It is difficult to gather enough data on recycling CFRP because research has only started in recent years. We have had to estimate energy intensity of recycled CFRP from limited information including the use of existing technology of virgin CFRP, interviewing resin companies, using data from studies of steel vehicles, and others. It, thus, is inevitable that the estimates include relatively much supposition under the present circumstances. We, however, can conversely say that target values of technological development are determined by comparison of data on the recycled CFRP and that on steel.

3.3.1 Reuse of thermosetting CFRP (CFRTS) As mentioned in the former section, using CFRP for chassis would be premised on reuse because the CFRP is high performance, has a long lifetime, and a large energy intensity. Processes required by reuse are transportation and washing at most. Energy intensity of these processes is generally extremely smaller than that of material production and molding. Energy intensity of reused CFRTS was about zero.

3.3.2 Recycle of CFRTS We would separate and recover carbon fiber (CF) from CFRTS after reuse, and then do a cascade recycle to CFRP for rigidity parts by adding thermoplastic resin. When fiber volume fraction is 30 %, weight ratio between CF and polypropylene (PP) was 0.462 : 0.538.

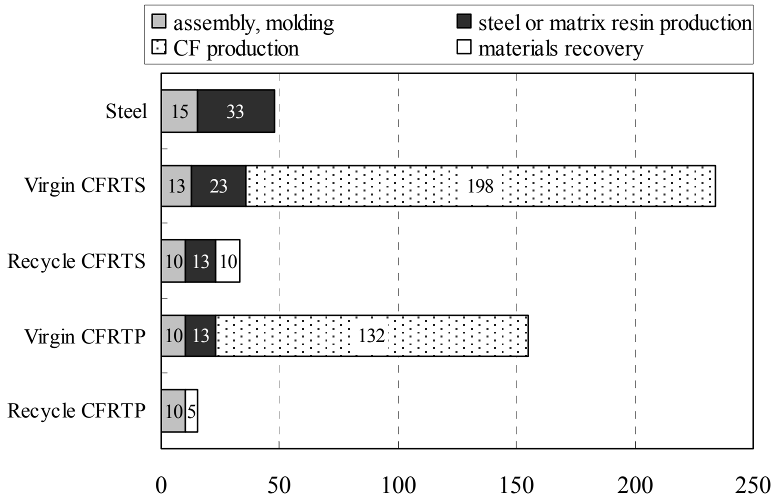

Fig.3 Energy intensity (MJ/kg) of virgin and recycled materials

Energy intensity of PP is 24 MJ/kg, so the energy consumption of added PP was 13 MJ/kg. Energy intensity of the preformed matched die molding is 10 MJ/kg. We estimated energy consumption of separating and recovering CF as 10 MJ/kg from study [5] about heat recovery and by interviewing resin companies. Therefore the energy intensity of the recycling CFRTS was 43 MJ/kg (Fig.3). Apart from the heat recovery, recovery by atmospheric pressure solution by using solvent is also studied.

3.3.3 Recycle of thermoplastic CFRP (CFRTP) We would directly melt and remold CFRTP after using without adding virgin resin. Energy intensity of the preformed matched die molding is 10 MJ/kg. We estimated energy consumption of recovering CFRTP as 5 MJ/kg because processes decrease as compared with the case of CFRTS recycling. Therefore the energy intensity of the recycling CFRTP was 15 MJ/kg (Fig.3).

4. CONCLUSION

We conclude that effective combination of several technologies, such as production rationalization, fast molding, and 3R, is needed in order to decrease energy intensity of CFRP parts for mass-produced cars to the level of steel parts. In particular, 3R has a great effect because energy intensity of virgin CFRP is very large and the technological development is indispensable.

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