THE DESIGN AND FABRICATION OF THE COMPOSITE-ALUMINUM HYBRID VEHICLE WHEEL BY USING ADHESIVE BONDING CONSIDERING MASS PRODUCTION

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1 Introduction

Fabric composites have good mechanical properties and excellent formability for fabricating complex shapes such as a dome and egg-box panels [1-3]. Because the vehicle wheels made of a fibrous composites have been proved to provide excellent mechanical performances such as high fuel efficiency many efforts have been made to accomplish the mass production of the composite wheels. But because of the complex geometry of the commercial wheels the fabrication method was limited, for instance, a resin transfer molding (RTM) process which inevitably needs complex custom hand assembly [4]. This problem was caused by the attempt to fabricate whole composite wheel structure in a single process. According to previous studies of wheel performance evaluation, the current wheels for passenger cars made aluminum alloy are known to have better gas mileage and design aspects relative to the wheels made of steel. Kim [5] investigated the vibration behavior of a aluminum wheel using frequency response function and compared this result with a steel wheel. Also, the vibrating traits based on the different design of the wheel and the structure (1 piece, 2 pieces, 3 pieces) were compared and as a result, he proved the excellence of the 2-piece and 3-piece wheels in terms of damping capacity. Wang et al. [6] analyzed fatigue behavior of a steel wheel and the analytic result was compared with the test result to confirm the mechanical performance of the wheel. Researches on the evaluation of the adhesive and composite fatigue life have been done. Kelly et al. [7] measured the fatigue life of hybrid type composite single-lap joints for design a wheel. Song et al. [8] investigated the failure strengths of composite single-lap adhesive joints with a consideration of various parameters. For about manufacturing process, they evaluated the substrate thickness effect on the structural performances. Jen et al. [9] performed various material tests with UD composite to estimate the strength of specimens according to the stacking angle using a modified Tsai-Hill criterion. Through various fatigue tests (tensile-tensile and compression-compression) of UD composite specimens fatigue life of the composites were experimentally investigated. They also proposed a formula that can estimate fatigue life of UD composite. Kim et al. [10] investigated the static compressive characteristic of various specimens (bias, sheared) of fabric composites to find out the effect on tow deformation on mechanical properties. Fatigue tests of various types of composite materials were carried out by experimental approaches to find out fatigue characteristics of composites under loading conditions. Kim et al. [11] predicted the fatigue life of the aluminum wheel using finite element analysis and fatigue test was also performed. The fatigue failure was predicted by the stress concentration calculated by the FEA.

In this paper, a composite-aluminum hybrid wheel composed of complex aluminum outer rim and a relatively simple shaped composite inner rim was introduced. By dividing the wheel structure into two parts, all the parts can be fabricated by the traditional mass production methods (compression molding for the composite inner rim and die-casting for the aluminum outer rim) and finally those two parts were bonded by adhesives. Consequently, the productivity can be increased resulting in the reduction of the production cost. To design the hybrid wheels the overall shape and dimension were fixed and only the bonding parts in the inner and the outer rim parts were modified. The bonding length and thickness were controlled to get the appropriate bonding strength under several performance tests such as the rotary bending test. Finite element analysis was carried out to determine the bonding thickness and length of the bonding part. For an effective bonding process a groove was machined at the bonding edge of the outer rim part which guaranteed the self-alignment of the two parts during assembling and bonding processes.

2 Experiments

2.1 Tensile test of the adhesive

Tensile tests of epoxy adhesives (Loctite 3128) were carried out in room temperature with the strain rate of 1.3mm/min using a universal testing machine (MTS810, USA). The Tensile tests were carried out following the ASTM D638. The stress-strain relations are shown in Fig. 1.

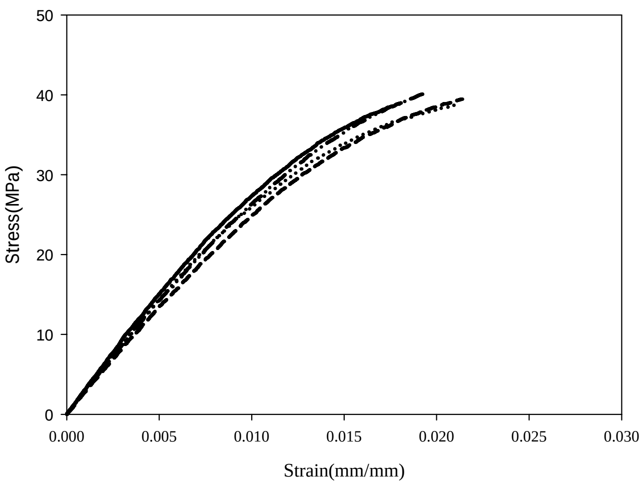

Fig.1 Stress-strain relationships for a epoxy adhesive (Loctite 3128).

2.2 Single lap joint test

To investigate the bonding strength of a composite-aluminum adhesive joint, single lap joint test was carried out with the strain rate of 1.3mm/min using a universal testing machine (MTS810, USA). The single lap joint test was carried out following the ASTM D1002 and D5868. To sustain the bonding thickness of 0.5 mm, a special bonding jig was used (see Fig. 2). The shape and dimension of the composite-aluminum single lap joint are shown in Fig. 3. The stacking sequence of the composite was $[0]_{nT}$.

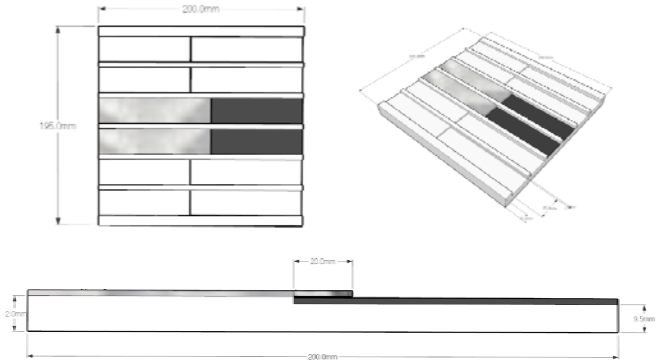

Fig. 2 Bonding jig

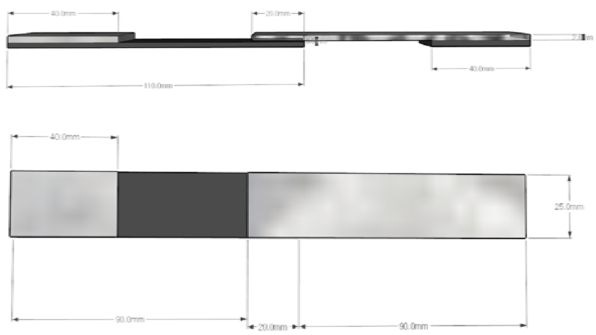

Fig.3 The composite-aluminum single lap joint specimen.

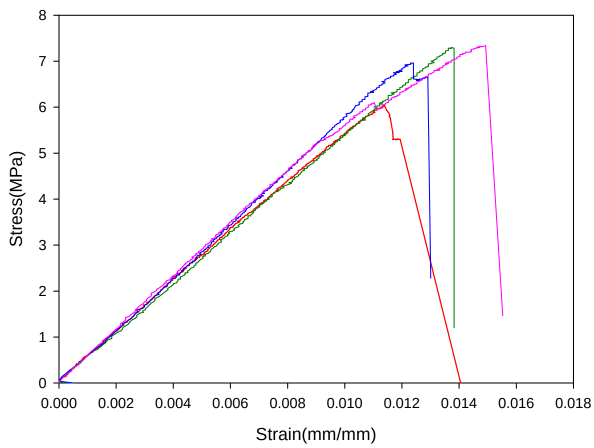

Fig.4 Test results from the single lap joint tensile test.

From the single lap joint test it was found that the stress-strain relationship was linear and the bonding strength was about 7 MPa as shown in Fig. 4.

3 FE Analysis

3.1 Material properties

The materials used in design of a aluminum-composite hybrid wheel were a aluminum T6061-T6, plain weave carbon /epoxy composite (WSN3k,SK), epoxy adhesive (Loctite 3128) and the material properties are listed in table 2 below.

Table 2 Material properties

Material	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's ratio
Aluminum	2700	68.9	0.3
	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
	276	310	17
Carbon/ epoxy	Density (kg/m^3)	E_x (GPa)	E_y (GPa)
	2700	70	70
	E_z (GPa)	ν_{xy}	ν_{xz}
	10	0.13	0.13
Carbon/ epoxy	ν_{yz}	X_t (MPa)	X_c (MPa)
	0.13	778	591
	Elongation (%)		
	1.8		
Adhesive	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's ratio
	1700	3.9	0.25
	Ultimate strength (MPa	Shear strength (MPa)	Elongation (%)
	38	7	2.3

3.2 Static bonding strength analysis

From the static lateral compressive analysis it was found that as the bonding thickness and length increased the stress level decreased to 1.50MPa which is much lower stress than the bonding strength measured by a single lap joint test. Table 3 lists the stress in epoxy adhesive according to the bonding thickness and bonding length.

Table 3 Generated maximum shear stress in the epoxy adhesive calculated by FEA.

Length \ Thickness	0.1mm	0.3mm	0.5mm
10mm	2.29MPa	1.91 MPa	1.72 MPa
20mm	1.82 MPa	1.83 MPa	1.73 MPa
30mm	2.30 MPa	2.03 MPa	2.13 MPa
35mm	1.75 MPa	1.61 MPa	**1.50 MPa**

3.3 Rolling rim fatigue analysis

The safety criterion of the rolling rim fatigue life is 2,000,000 cycles. To perform the rolling rim fatigue analysis the cosine distributed loading condition at a part of the rim in radial direction was imposed to simulate the actual driving condition as shown in Fig. 5. The maximum stresses in epoxy adhesive and composite material were calculated according to the bonding thickness and length and those values were used to estimate fatigue life of the each material.

From the analysis result it was found that the generated stress levels in all the materials such as epoxy adhesive, composites were low enough for the structure to resist over 2,000,000 cycles. (Table 4)

Table 4 Result of rolling rim analysis (composite-aluminum hybrid wheel)

Aluminum part (310MPa)	Adhesive layer (von mises) (35MPa)	Adhesive layer (shear) (7.0MPa)	Composite part (591MPa)
78.36	1.726	0.2997	17.96

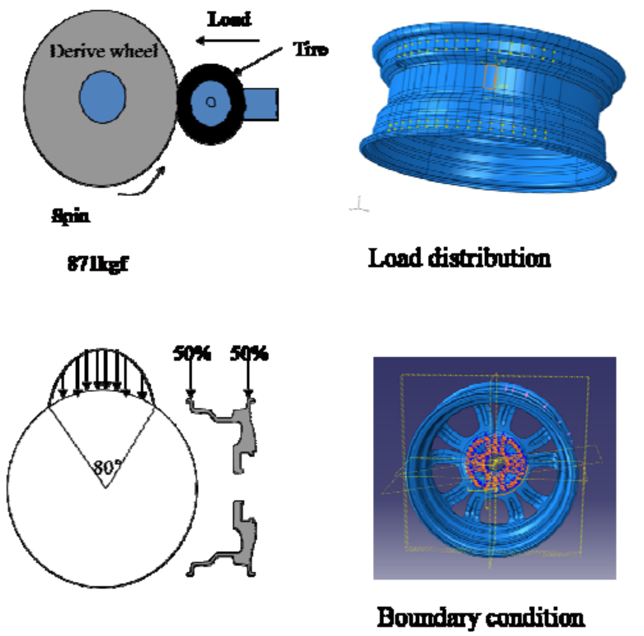

Fig.5 Rolling rim fatigue analysis

From the finite element analyses the bonding length and the thickness were determined to be 35mm and 0.5 mm, respectively.

4 Fabrication of the hybrid wheel

A 4-piece aluminum mold was prepared to fabricate a composite inner rim as shown in Fig. 6.

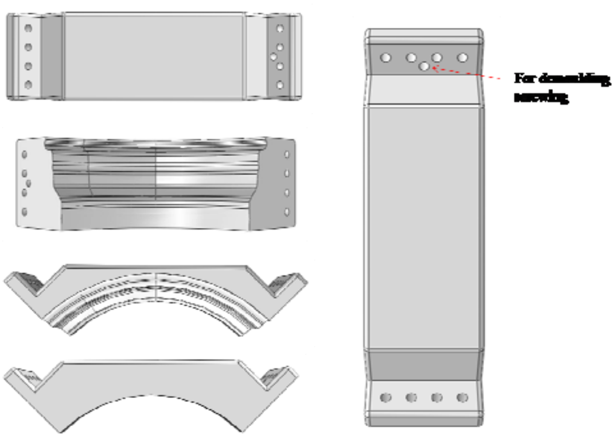

Fig. 6 Aluminum mold for fabricating composite inner rim.

After the parts of the mold were assembled, the composite prepregs were stacked inside the mold surfaces and then cured in an autoclave using vacuum bag de-gassing molding process (see Fig. 7). And then the aluminum out rim was bonded using epoxy adhesive with 0.5 bonding thickness after the surface treatment with abrading papers for enhancing bonding strength. Outer rim was designed to have a bump, which is to be matched with a groove formed in the composite inner rim, for self-alignment during bonding process.

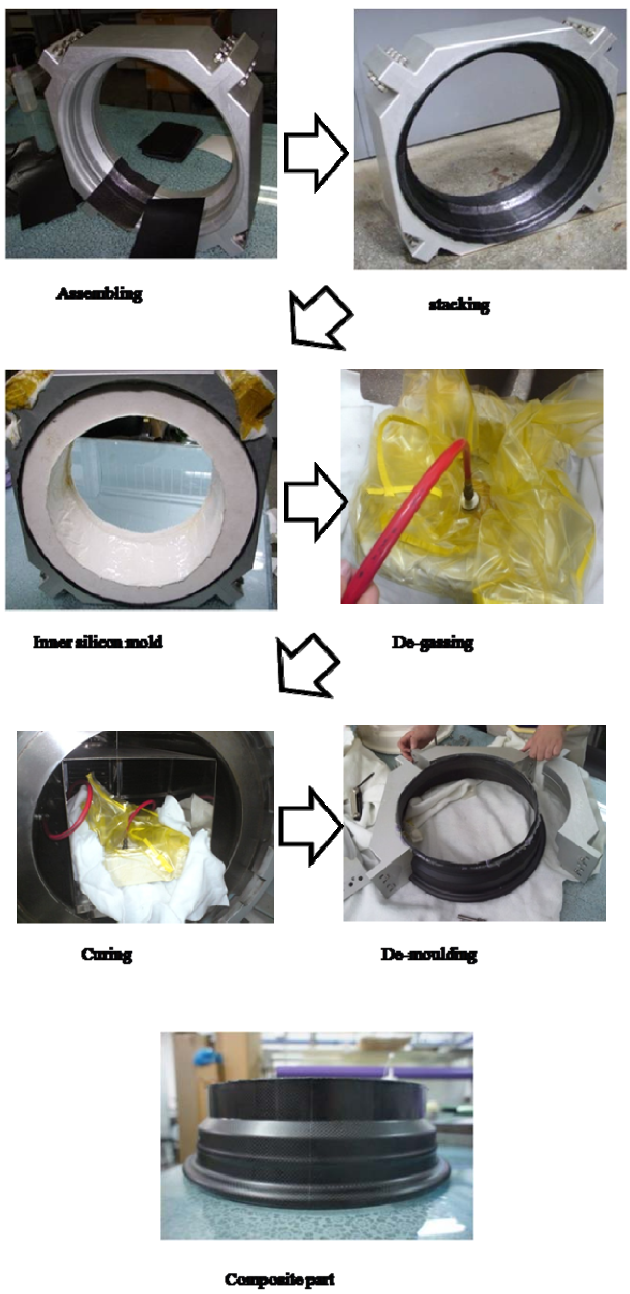

Fig.7 Fabrication of the composite inner rim.

5 Conclusion

This study suggests a method to fabricate composite-aluminum hybrid vehicle wheels in mass production by adhesive bonding method. The tensile tests of adhesives were carried out for FE analysis. Also, to investigate the shear strength of a joint, single lap joint tests were carried out. It has been shown that the wheel had the best performance when the bonding length and thickness were 35mm long and 0.5mm thick, respectively. Under this condition, various analyses such as a rolling rim fatigue analysis were carried out. Based on the FE analysis results the prototype of the composite inner rim was fabricated by an autoclave de-gassing molding process. On the surface of the aluminum outer rim a bump was designed to be matched with the groove on the surface of the composite inner rim was machined out for the self-alignment during assembling and bonding process of the inner and outer rims. The weight of the overall wheel structure decreased by 10% and this was expected to improve gas mileage. From the rolling rim analysis result it was found that the hybrid wheel had about 400% higher compliance than that of conventional aluminum wheel with the same size, which provides better riding comport. From this study the mass production method for composite-aluminum hybrid wheels was proposed and the mechanical performances were evaluated by using FE analysis.

References

[1] S.H. Yoo, S.H. Chang and M.P.F. Sutcliffe, "Compressive characteristics of foam-filled composite egg-box sandwich panels as energy absorbing structures". *Composites Part A: Applied Science and Manufacturing*, Vol. 41, No. 3, pp 427-434, 2010.

[2] S.H. Yoo, S.W. Park and S.H. Chang "An experimental study on the effect of tow variations on compressive characteristics of plain weave carbon/epoxy composites under compressions". *Composite Structures*, Vol. 92, No. 3, pp 736-744, 2010.

[3] J. G. Chung and S. H. Chang, “Changes in Tow Geometry of Plain Weave Carbon/Epoxy Fabrics Draped onto Compliant Hemisphere Molds”, *Polymer Composites*, Vol. 27, No. 2, pp. 111-118, 2006.

[4] P.J. Kim and D.G. Lee. “Improvement of surface quality and development of composite wheel for passenger cars manufactured by RTM. *Proceeding of conference on KSPE*, Jeju, Korea, pp.54-57, 2003.

[5] B.S. Kim. “An study on vibration characteristics of automobile al-alloy wheel”**.** *Transactions of the Korean Society of Machine Tool Engineers***,** Vol. 14, No. 3, pp-122-127, 2005.

[6] X. Wang and X. Zhang. “Simulation of dynamic cornering fatigue test of a steel passenger car wheel”. *International journal of fatigue*, Vol.32, No.2, pp.434 - 442, 2010.

[7] Kelly G. “Quasi-static strength and fatigue life of hybrid(bonded/bolted)composite single-lap joints”. *Composite structures*, Vol. 72, No. 1, pp.119 - 129, 2006.

[8] M. G. Song, J.H. Kweon , J.H. Choi, H.J. Kim, Song M.H. and S.J. Shin . “Strength of Composite Single-lap bonded joints with various manufacturing processes for aircraft application” *Journal of the Korean society for aeronautical & space sciences* Vol.37 No.8 pp.751-758, 2009.

[9] M.H.R Jen and C.H Lee. “Strength and life in thermoplastic composite laminates under static and fatigue loads. ParⅠ; experimental”. *International journal of fatigue* Vol. 20 No. 9, pp.605-615, 1998.

[10] S.J. Kim and S.H. Chang “The effect of micro-geometry of fabric composites on compressive characteristic”. *Proceeding of 8th international conference on textile composites*, Nottingham, UK; 2006.

[11] M.S. Kim, K. J. Ko, J.H. Kim, C.G. Yang and K.M. Kim “ The study of the fatigue life prediction on wheels through CAE”. *Transactions of Korea society of automotive engineers* Vol.12, No, 2, pp.117-122, 2004.