Material Design of Al/CFRP Hybrid Composites for the Hull of Autonomous Underwater Vehicle

Yun Hae Kim
Korea Maritime University
1 Dongsam-dong, Youngdo-gu
Busan, 606791 Republic of Korea
Young Dae Jo
Korea Maritime University
1 Dongsam-dong, Youngdo-gu
Busan, 606791 Republic of Korea
Sung Youl Bae
Korean Register of Shipping
60 Sinseongno, 23-7 Jang-dong, Yuseong-gu
Daejeon, 305343 Republic of Korea
Seok Jin Sin
Korea Maritime University
1 Dongsam-dong, Youngdo-gu
Busan, 606791 Republic of Korea

***Abstract*-The AUV(Autonomous surface vehicle) is widely used for military purpose and scientific purpose. The AUV can save human life from severe environment and reduce the operating cost of underwater equipment. Generally, hulls of AUV are made of composite materials or metal alloys such as aluminum alloy and titanium alloy. Composite materials are well known as its light weight, corrosion resistance and freedom of shape design. But, composite materials are not have plastic deformation so this can be a disadvantage as the materials for underwater equipment. From this reason, this study focused on the reliability of the material. This study contains material design, experiment for materials and verification by FEA. The material what was focused on this study is Al-CFRP hybrid composites. There are used two kinds of Al-CFRP hybrid composites. Inter laminar property between Aluminum alloy and carbon fiber reinforced composites is very important. So, two kinds of Al-CFRP were used for this study. One is co-cured material and the other is post-bonded. Tensile and interlaminar test were achieved to define material properties. Profits from use of Al-CFRP sandwich material are like these. First, this material can enhance the buckling performance and second, it can achieve the reliability against failure at a moment. Mechanical tests are achieved for designed materials and its results are used for FEA. This study verify the feasibility about Al-CFRP hybrid composites for AUVs. The hull of AUV manufacturing and ocean diving test will be achieved in future work.**

I. INTRODUCTION

The AUV(Autonomous surface vehicle) is operated for using natural resources and military purpose. Natural resources such as oil, natural gas, and ores from deep see have limited amount and gathering resources will be focused on the sea. The AUV is a useful equipment to save human life from severe underwater conditions[1]. And the AUV is well known for an important unmanned vehicle for military operations. The AUV can save soldier's life from various dangerous. The AUV is a multi role system. Reconnaissance, anti-surface warfare, anti-underwater warfare and mine hunting are missions of the AUV. The AUV can reduce operating cost and it can achieve the most effective result. From these reason, many countries trying to develop more advanced system[2].

Most of underwater equipment need pressure resistant property because they are usually operated deep underwater. The pressure resistant technology requires several detail engineering technologies - design and manufacturing of pressure resistant chamber, pressure resistant of exposed sensors, pressure resistant of working component such as the manipulator and water proof system for the propel component[3]. The aluminum and the titanium are used for the materials of the AUV's hull and sometimes composites are used for it.

Design skill for the AUV is good but composites design skill for the AUV is not enough. There are so many concepts for using composites to naval equipment such as the ship or the submarine. The reasons of these concepts are based on the advantage of composites. Composites are light and strong. It can enhance the performance of naval equipments. Composites come from the aerospace technology. Many material engineers are trying to make better composites by metal/composites hybrid. Several properties metal/composites hybrid material such as fatigue or impact resistant are better than normal composites[4-7]. ARALL(Aramid fiber reinforced aluminum), GLARE(Glass fiber reinforced metal) and DRA(Double-layer aluminum/discontinuously reinforced aluminum are examples of metal/composites hybrid

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

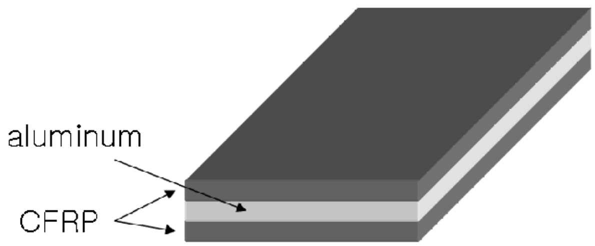


Fig. 1 Scheme of Al/CFRP hybrid composites

Fig. 2 Appearance of the NUWC's AUV Manta

Fig. 3 Appearance of the ISiMI

materials[8]. Aluminum/CFRP hybrid materials are used for the AUV's hull. The schematic of Al/CFRP is shown in Fig. 1. Material tests and FEA(Finite element analysis) were achieved. This study shows the possibility of Al/CFRP hybrid materials for the AUV's hull.

II. Types of AUV

The AUV is not only unmanned system but autonomous system. It can be operated by wireless control and it can be operated by itself. Its command base can be the ship, the submarine and the airplane. Shapes of AUVs divided two types - torpedo type and marine animal type.[2].

The torpedo type is general shape of the AUV because it can be launched from submarine's torpedo tube and water resistance is small. TheNUWC Manta - the AUV of marine animal type - is shown in Fig. 2. The ISiMI - the torpedo type - is shown in Fig. 3. The torpedo type is used for this study.

III. Material Design

A. *Material requirement*

The AUV is operated on the deep sea and the shallow sea. Requirements of the AUV depend on these operation areas. Operating condition is assumed 5,000 m depth, so 50 MPa of pressure is applied to the AUV's hull.

Fracture of the AUV can be caused by material failure or buckling of the hull. Material failure will be occurred if thickness of the hull is thin. And buckling is the case of thick thickness[9].

If fracture of the AUV is caused by material failure the maximum stress of material is shown in Eq. 1 and material failure will start from inside of the pressure chamber, so Eq. 1 can be simplified as Eq. 2[10].

$$\sigma = \frac{-qa^2(b^2+r^2)}{r^2(a^2-b^2)} \tag{1}$$

$$\sigma_{\max} = \frac{-2qa^2}{(a^2-b^2)} \qquad r = b \tag{2}$$

q: external pressure
r: radius
a: outside radius
b: inside radius

There are many theories about fracture with buckling. Von-Mises's thin wall equation was used in this study[9]. According to this equation, allowed pressure is determined by Eq. 3 and it can be simplified as Eq. 4.

$$q' = \frac{E\frac{t}{r}}{1+\frac{1}{2}\left(\frac{\pi r}{nl}\right)^2}\left\{\frac{1}{n^2\left[1+\left(\frac{nl}{\pi r}\right)^2\right]^2} + \frac{n^2t^2}{12r^2(1-\nu^2)}\left[1+\left(\frac{\pi r}{nl}\right)^2\right]^2\right\} \tag{3}$$

$$q' = \frac{0.92E}{\left(\frac{l}{r}\right)\left(\frac{r}{t}\right)^{2.5}} \tag{4}$$

E: elastic modulus
r: radius
n: number of Lobe
l: length
t: thickness
q': allowed pressure

Table 1. Properties of materials

Properties	Carbon fiber	Glass fiber	Epoxy resin
Tensile strength (MPa)	2,530	2,500	130
Elastic modulus (GPa)	230	74	4.5
Density	1.8	2.6	1.2
Poisson's ratio	0.35	0.25	0.4

Table 2. Mechanical properties of Al/CFRP hybrid composites

Properties	Al/CFRP hybrid composites
Tensile strength (MPa)	323
Flexural strength (GPa)	344

B. Theory of composites

Composites are consisted of matrix and reinforcement. The role of matrix is distribution of applied load. The strength of composites depends on the reinforcement, so the FVF(Fiber volume fraction) is an important factor. The FVF can be calculated by Eq. 5. The mass is better than the volume for measurement, so Eq. 5 can be translated as Eq. 6.

$$V_f = \frac{Volume\ of\ fiber}{Total\ volume} \tag{5}$$

$$V_f = \frac{\frac{M_f}{\rho_f}}{\frac{M_f}{\rho_f} + \frac{M_m}{\rho_m}} \tag{6}$$

The strength and the modulus can be calculated from these equation.

$$E_1 = E_f V_f + E_m V_m \tag{7}$$

$$\sigma_1 = \sigma_f \left[V_f + (1 - V_f)\frac{E_m}{E_f} \right] \tag{8}$$

The FVF of composites can be controlled but the most effective FVF is known as 70%. The possible FVF can be changed if the manufacturing process is different. So, the manufacturing process have to be considered. Composites manufacturing processes such as the autoclave process which is generally used for aerospace, VARTM(Vacuum assisted resin transfer molding) which is generally used for large structures such as wind turbine blade, RTM(Resin transfer molding) which is the most suitable process for large quantity production, and hand lay-up which is the most cheap process have a different FVF. The FVF of autoclave is about 60~70%, VARTM is about 70%, and RTM is about 50%. The FVF of the hand lay-up process has a big deviation from a person or working conditions, so the hand lay-up is not good for the AUV's hull.

In this study, the thickness of the hull is limited to 25 mm. Because T.H. Jouung define the optimized thickness of aluminum alloy and titanium alloy as 17 mm, 10 mm. The strength of 25 mm composites is similar with 17 mm aluminum alloy and 10 mm titanium alloy. The composites hull will not heavier than aluminum alloy and titanium alloy if the thickness is less than 25 mm.

C. Composites design

In this study, autoclave process is used for manufacturing. Because composites that was made by autoclave show the most property. Carbon fibers and aluminum 6061 were used for hybrid composites. The AUV is operated underwater, so water absorption was considered. For this reason, 177C cure epoxy resin was used for matrix. It is the most resin system for water absorption. Reinforcement fibers were plain weaved. Mechanical properties of materials are shown in Table 1.

The tensile strength and the modulus were defined as 416 MPa and 57 GPa. It was calculated by Eq. 2 and Eq. 4. Properties on the table 1, Eq. 7 and Eq. 8 were used for material design.

IV. VERIFICATION OF MATERIAL DESIGN

A. Material test

Tensile test and bending test were achieved according to ASTM D 638 and ASTM D 2344. Table 2 shows the result of tests.

Tensile strength of Al/CFRP hybrid composites is similar with aluminum. Material failure is start from surface layer. Because the thickness of CFRP layer is not enough to enhance the tensile strength. Flexural strength of Al/CFRP hybrid composites is higher than aluminum or CFRP. The aluminum and the CFRP are consisted like sandwich structure.

B. Geometry modeling of the hull

In this study, the torpedo type AUV was designed for material design and the 3D model is simplified. The 3D geometry is designed by CATIA V5 and it is shown in Fig. 4.

C. Structural analysis by FEM

The thickness of the pressure chamber is different if operating depth is different. Own weight of pressure chamber will be a pressure to itself when the depth is high. It can affect to maneuverability and speed. So, material selection and structure analysis is important for the AUV[신장용 1999].

Structural analysis is achieved by ANSYS V11. The element which was used here is SOLID 191. The result of this analysis is shown in Fig. 5. According to the result of analysis, deformations of each cases are 1.16 mm, 0.88 mm. The

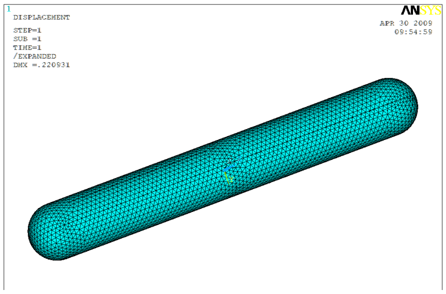
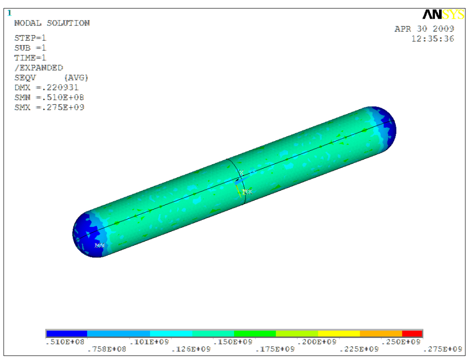
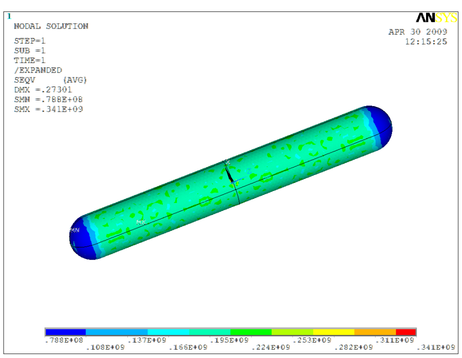


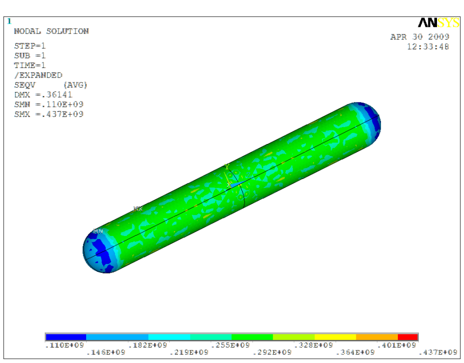
Fig. 4 FE model of the simplified AUV



(a) Stress contour of the aluminum alloy AUV



(b) Stress contour of the composites AUV



(c) Stress contour of the hybrid composites AUV

Fig. 5 FEM result of each case

pressure that applied to the AUV is similar with bending condition. The Al/CFRP hybrid composite material can be the effective material for the AUV's hull.

V. CONCLUSION

Al/CFRP hybrid composites are designed by theoretical calculation and achieved mechanical tests. Results of mechanical test and structural analysis are sum up to below.

1) To prevent material failure and buckling, 416 MPa of tensile strength and 57 GPa of modulus are required for the AUV's hull.

2) The AUV is a underwater equipment. 177 C cure epoxy resin system was used to prevent water absorption.

3) Al/CFRP hybrid composites are good to bending load condition.

4) Tensile strength of Al/CFRP can be enhanced if the thickness of CFRP is higher.

5) According to the result of structural analysis, Al/CFRP is better than aluminum alloy or CFRP.

In this study, aluminum and carbon fiber were directly bonded. But it is dangerous because it can make a corrosion. At least, one layer of glass fiber have to be placed between aluminum and CFRP to prevent this problem.

ACKNOWLEDGEMENT

This research was financially supported by the Ministry of Education, Science Technology (MEST) and Korea Industrial Technology Foundation (KOTEF) through the Human Resource Training Project for Regional Innovation.

REFERENCES

[1] T. H. Joung, C. M. Lee, S. W. Hong, J. B. Kim and C. W. An, "A study on the results of the pressure vessel design, structural analysis and pressure test of the semi-autonomous underwater vehicle" *Journal of Ocean Engineering and Technology,* vol. 18 No. 4, pp. 52-58, 2004.

[2] S. H. Yun, Review: Development of the AUV in US navy, *Hapcham* vol. 19, 2002, pp.194-205.

[3] S. Jang, "Preview: Development of ship building industry" *Chosunkongup,* vol. 172, pp. 24-49, 1997

[4] H.W. Nam, J. H. Park, W. Hwang, and K. S. Han, "Stacking sequence design of fiber-metal laminate composites for maximum strength" *Journal of the korean society for composite materials*, vol. 12 No. 4, pp. 42-54, 1999

[5] M. Kawai, A. Hachinohe, K. Takumida, and Y. Kawase, "Off-axis fatigue behaviour and its damage mechanics modelling for unidirectional fibre-metal hybrid composite: GLARE 2" *Composites Part A*, Vol. 32, pp. 13-23, 2001

[6] G.C. Papanicolau, D.J. Bakos, and Th.V. Kosmidou, "Effect of the interface stiffness and skin-core adhesion efficiency on the interfacial

stress distribution of sandwich structures" *Composites Part A*, vol. 38, pp. 1099-1106, 2007.

[7] M. Kawai, Y. Arai, "Off-axis notched strength of fiber-metal laminates and a formula for predicting anisotropic size effect", *Composites Part A.* Vol. 40, pp. 1900-1910, 2009.

[8] Stephan Hinz, Toshihiro Omoori, Masaki Hojo and Karl Schulte, "Damage characterisation of fibre metal laminates under interlaminar shear load", *Composites Part A.* Vol. 40, pp. 925-931, 2009.

[9] Warren C.Y., "Roark's formulas for stress and strain", *McGraw-Hill Inc.,* pp. 519, 638-639, 690, 1989.

[10] T. H. Chung, I. S. Nho, P. M. Lee, and Y. C. Lim, "Design optimization of pressure vessel of small autonomous underwater vehicle", *Journal of Ocean Engineering and Technology.* Vol. 19 No. 1, pp. 95-99, 2005.