CSCanada
Advances in Natural Science
Vol. 7, No. 4, 2014, pp. 1-8
DOI:10.3968/6129

ISSN 1715-7862 [PRINT]
ISSN 1715-7870 [ONLINE]
www.cscanada.net
www.cscanada.org

[1]Overviews of Investigation on Submersible Pressure Hulls

ZHANG Jian[a],[b]; ZUO Xinlong[a],*; WANG Weibo[b]; TANG Wenxian[a]

[a]Jiangsu University of Science and Technology, Zhenjiang, China.
[b]Chinese Ship Scientific Research Center, Wuxi, China.
* Corresponding author

Received 28 September 2014; accepted 22 November 2014
Published online 26 December 2014

Abstract
With the exploration of natural resources and the research on oceanography in the deep sea obtained more and more attention, in the recent years, the pressure hull of the submersibles has been widely studied and used in many states. In order to the continuing design and assessment on it effectively, the paper summarizes the design method, the structural feature and the material selection of this object.

Key words: Pressure hull; Submersible; Design method; Structural feature; Material selection

ZHANG Jian, ZUO Xinlong, WANG Weibo, TANG Wenxian (2014). Overviews of Investigation on Submersible Pressure Hulls. *Advances in Natural Science*, *7*(4), 1-8. Available from: http://www.cscanada.net/index.php/ans/article/view/6129
DOI: http://dx.doi.org/10.3968/6129

INTRODUCTION
When submerged depth is 6000 meters, the operation field of submersible covers more than 95% of the ocean floor, as shown in Figure 1. In recent years, a lot of research and experiment of submersible were carried out, and obtained a lot of achievements. The autonomous underwater robot without cable, whose working depth was up to 6000 meters, has been successfully developed in China. On July 28, 2011, the manned submersible named "JiaoLong" with maximum working depth of 5188 meters was tested well, which indicates operation scope beyond 80% of the ocean floor and a symbol of Chinese dive technical breakthrough (Ma, 2012; MacKay, 2012).

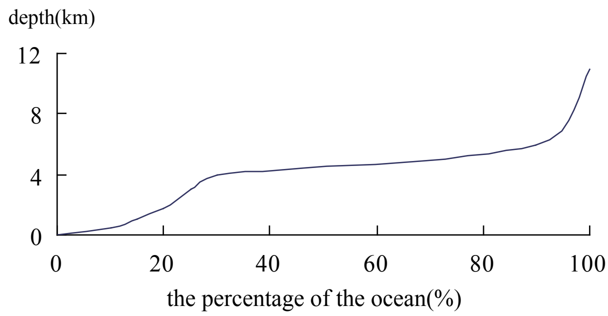

Figure 1
The Relationship Between Ocean Depth and the Corresponding Covering Ratio of Floor

The submersible consists of the outer hull meeting the requirement of hydrodynamic and the pressure hull providing atmospheric pressure space for crew and equipment. Pressure hull accounting for 25%-50% of the submersible total weight, as the main provider of buoyancy working on the submersible, construct a watertight space, which ensures a relatively changeless internal pressure during the process of diving (Reynolds, Lomacky, & Krenzke, 1973). Thus, the properties of pressure hull, such as yield strength, the stability, local strength on crack and fatigue strength, affect the submersible overall performance directly.

In this paper, the survey of the existing pressure hull was summarized with respect to the design method, structural feature and specific material. The merits and demerits of these properties were listed and compared, and the index of the assessment checking the quality of submersible was proposed, which has important significance for the consequent study of pressure hull.

[1] Corresponding author. Zuo Xinlong, Male, 1991, Post-Graduate, Research on mechanical manufacture and automation major, E-mail:zuoxinlong163@163.com

1. THE DESIGN OF PRESSURE HULL

The items of design concerning pressure hull consist of structural design, material selection, and assessment of stress distribution and stability (Fan, 2008). The influencing factors, including buoyancy coefficient (the ratio of the weight and tonnage), the requirement of internal layout and manufacturing process, failure modes, working depth, safety factor and so on, should be taken into account. In general, the assessment of the pressure hull's performance could be evaluated from four aspects: buoyancy coefficient, the structural strength, the ratio of internal space occupancy and hydro-dynamic resistance. The design process of pressure hulls as shown in Figure 2, which could improve the work efficiency, shorten the working period, simplify logistical support, and reduce the cost of development effectively. The main directions of the existing study include: reducing weight (improve buoyancy coefficient), increasing the ratio of internal space occupancy and reducing hydro-dynamic resistance.

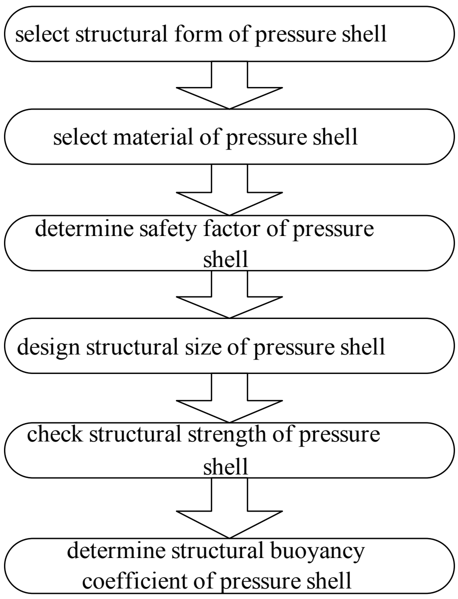

Figure 2
The Design Process of Pressure Hull

A lot of design specifications for pressure hull have been proposed, and various specifications' contents were not same, which making the calculation results different. J. Odland analyzed the specification of DNV submersibles and underwater system carefully, and proposed that the specification, which gave the strict calculation method, the limited states and applicable condition about the structure of column hull, conical hull, spherical hull, hemispherical hull, qusi-spherical hull, ellipsoid hull, frame, bulkhead, etc. The limited states of stress for spherical hull and conical hull of the small submersible was proposed by Lloyd's Register's "Submersible structure, classification, regular inspection specification". A. Harry studied the design specification of pressure hull briefly. Cha Huanfeng calculated the welded cylindrical hull according to the four specifications: DNV, ECCS, API Bull, ASME.

2. THE STRUCTURE OF PRESSURE HULLS

The pressure hull structural forms of submersible include: spherical structure, ellipsoidal structure, cylindrical structure, the toroidal structure and composite structure, as shown in Figure 3. Spherical structure and cylindrical structure are generally adopted by existing submersibles. Following is a brief analysis for the characteristics of these structures (Zhu, 1992; Shi, & Li, 1991; Liang, 2006; Ness & Simpson, 2000).

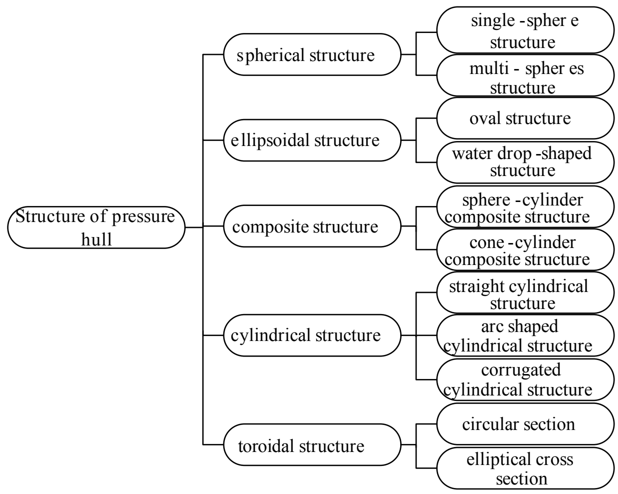

Figure 3
Structural Classification of Pressure Hulls

2.1 Spherical structures

Spherical hull is highly symmetrical thin pressure structure, and the stress of the each part is equal under uniform pressure, indicating that it has good performance on strength properties. The optimum buoyancy coefficient and stability for spherical hull can be got. The stress calculated from the spherical hull is half of that calculated from the cylindrical hull of the same diameter, and the ratio of the surface area and volume is small, which make the material fully utilized (Cheng, 2012). However, its rate of the internal space occupancy is lower, which is not conducive to the cabin layout. Even though spherical volume will be added with increasing the diameter, it will amplify the resistance of movement and reduce the speed of the submersible.

2.1.1 Single-Sphere Structure

The pressure hull of single-sphere structure has been widely used (Figures 4-5). In addition to the above common advantages, the structure is easy to be manufactured and be cut for hatches, portholes, and cable grommet hole, and convenient to carry out the stress analysis (Pan, 2010).

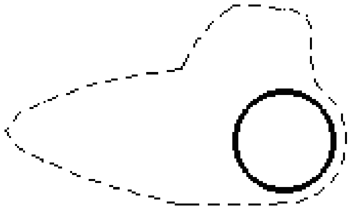

Figure 4
"Deep-Sea 2000" Submersible

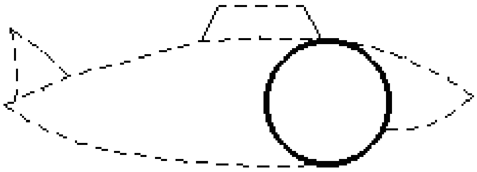

Figure 5
"Alvin" Submersible

2.1.2 Multi-Spheres Structure

Multi-spheres structure is composed of two or more isolated balls, which increases interior space to a certain extent, ensures better shape and reduces its hydrodynamic resistance. The submersible "Deep investigation" and "DSRV" is the typical application, as shown in Figure 6-7.

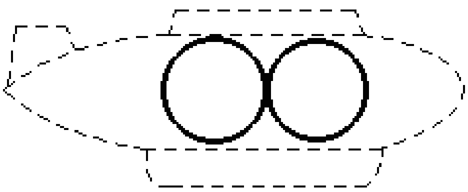

Figure 6
"Deep Investigation" Submersible

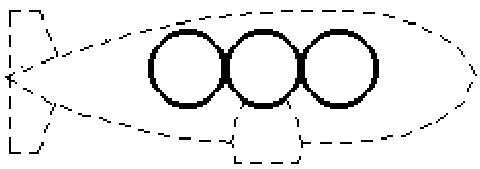

Figure 7
"Dsrv" Submersible

2.2 Cylindrical Structure

Cylindrical pressure hull is relatively easy to be manufactured. Its space utilization is satisfied, and internal cabin is easy to layout. The disadvantage of this structure exists, such as, large buoyancy coefficient, the weak hull with welded internal additional ribs, the lower material utilization, and the poor overall stability. In addition, the peripheral stress is twice than the axial portion, and the bending stress at the ends and transition region of the cylindrical hull is obvious.

2.2.1 Straight Cylindrical Structure

The internal structure of straight cylindrical is divided into unribbed structure (Figure 9-10) and ribbed structure, which is shown in Figure 8. The advantages of stiffener structure generally include excellent hydrodynamic performance, better internal arrangement, lighter external structure and lower construction costs. The smoothly unribbed cylinder sometimes is used by pressure hull. The stability of cylindrical portion can be guaranteed by hull thickness when the diameter, the length and the external pressure are small. Ribbed structures can be divided into inflatable tube ribbed structure (Figure 11) and ring ribbed structure (Figure 12-13) (Fathallah, Qi, Tong, & Helal, 2014).

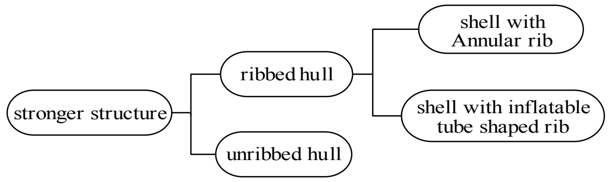

Figure 8
Stronger Structure of Cylindrical Hull

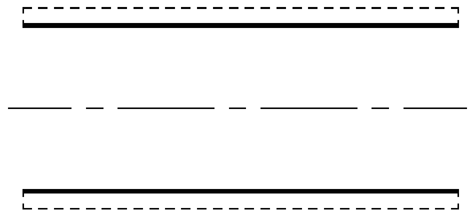

Figure 9
Unribbed Cylindrical Hull

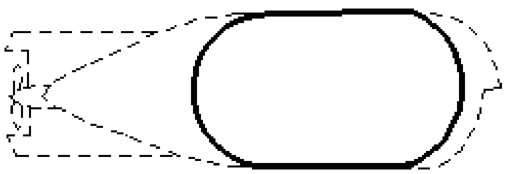

Figure 10
"Aliminant" Submersible

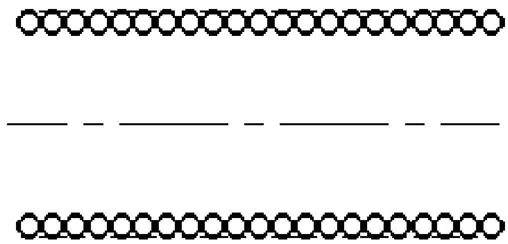

Figure 11
Cylindrical Hull With Inflatable Tube Shaped Rib

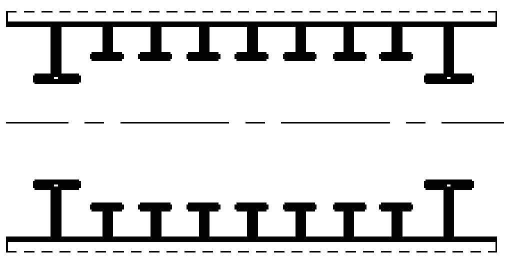

Figure 12
Cylindrical Hull With Ring Rib

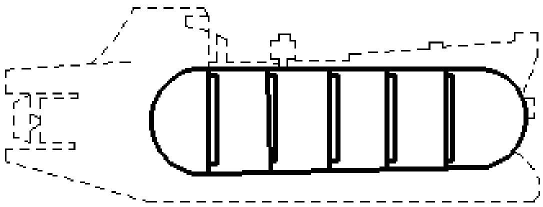

Figure 13
"Aluminan" Submersible

2.2.2 Arc Shaped Cylindrical Structure

Arc shaped cylindrical structure, developing from straight cylinder, can increase the strength of the hull, avoid the large stress of hull's middle part, and also reduce hydro-dynamic resistance (Burcher & Rydill, 1994). The structure is similar to the ellipsoid structure, because the stress concentration at both ends does not happen easily, and it is also conducive to the spatial arrangement (Figure 14).

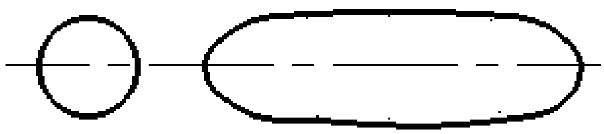

Figure 14
Curved Cylindrical Hull

2.2.3 Corrugated Cylindrical Structure

Corrugated cylindrical structure is shown in Figure 15 and 16. The hull of this structure can be manufactured in the form of segments, so the productivity is improved. Meanwhile, each segment can keep changeable shape according to the specific requirement. For instance, Ross made the segment to be the tapered section. Spherical segment is better than conical section in theory. It is obtained from the corresponding test that spherical segment has good performance on the aspect of the anti-extrusion (Blachut & Smith, 2008).

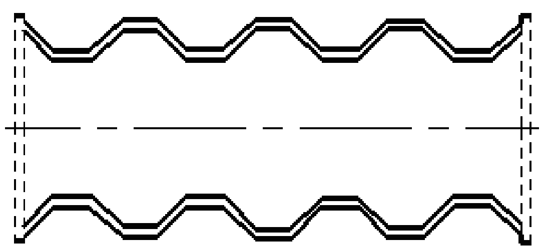

Figure 15
Corrugated Cylindrical Hull

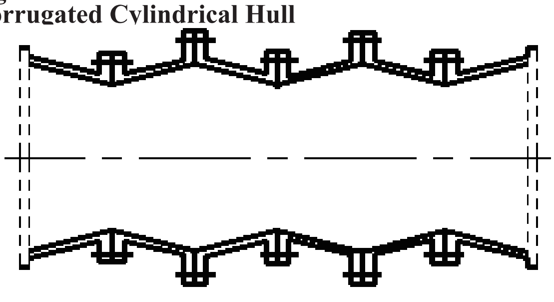

Figure 16
Segmented Corrugated Cylindrical Hull

2.3 Ellipsoidal Structure

Ellipsoidal structure is a compromise of cylindrical structure and spherical structure，whose section is similar to an ellipse. It's high space occupancy rate is conducive to the layout of the cabin. Both ends and middle part of ellipsoidal structure like a sphere, and the interval is shaped smoothly. This kind of structure can avoid stress concentration by making the whole surface of pressure hull have the equal stress. Furthermore, the shape of the structure is better streamlined and helps to reduce the resistance of water (Ma & Cui, 2005; Ma & Cui, 2004; Liang & Chen, 2004).

2.3.1 Oval structure

Pressure hull with oval cross section has appropriate buoyancy coefficient. On a submersible, this coefficient is as important as structural strength. Optimizing structure could cut down the weight in order to make the submersible bear more load and travel further in the distance. Oval structure is better streamlined, it can reduce not only the resistance of water greatly to improve the speed and flexibility of the submersible, but also energy consumption. Secondly, this kind of structure is conducive to the arrangement of internal space and getting larger space occupancy rate. Pressure hull with elliptical shape has the same character of thin spherical hull stress. It can avoid bending caused by stress concentration and be convenient to install penetrating structure through the hull which can improve the stability of submersibles. As shown in Figure 17, submersible SP-350 utilizes the pressure hull with oval cross section. However, the structure costs too much, and it's hard to analyze its stress (Zhu & Wu, 2002).

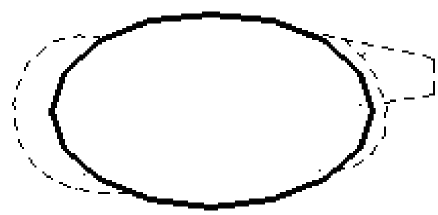

Figure 17
"SP-350" Submersible

2.3.2 Water-Drop Shaped Structure

Water-drop or needle shaped structure (as shown in Figure 18) is the best streamlined shape, and has the highest propulsive efficiency. It's appropriate for the submersible to sail in high speed, so it will be the main orientation of efforts to improve the performance of submersible. However, the structure can cause flexural stress easily, especially at the tip of the hull.

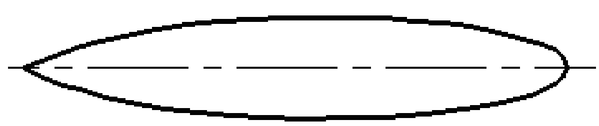

Figure 18
Teardrop Shaped Hull

2.4 Toroidal structure

Toroidal structure is similar to the shape of swimming lap, which can reduce its buckling pressure to the minimum. Figure 19 shows the pressure hull is formed by a circular section spinning on an axis. Figure 20 shows the pressure hull is formed by an oval section spinning on its central axis at a certain angle *γ*(in Figure 21, *γ*=0; in Figure 22,*γ*=90). In the description of this structure, *r* represents radius of section, and R represents the radius around the axis (Blachut & Jaiswal, 2000; Qu, 2012; Blachut, 2004).

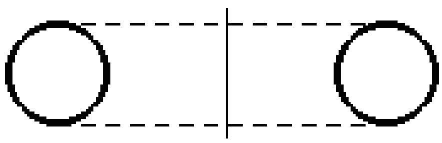

Figure 19
Toroidal Hull With a Circular Section

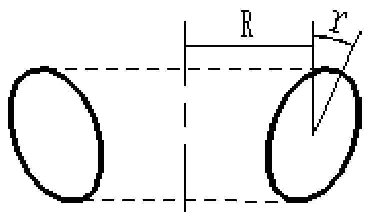

Figure 20
Toroidal Hull With Elliptical Cross Section At An Angle *γ*

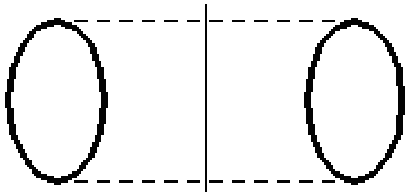

Figure 21
Toroidal Hull With Elliptical Cross Section at an Angle 0

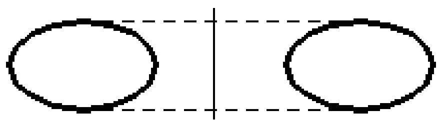

Figure 22
Toroidal Hull With Elliptical Cross Section at an Angle 90°

2.5 Composite Structure

Composite structure is consisted of two or more kinds of hull, which makes up for the shortcomings of single kind. The existing pressure hulls of submersibles are mainly sphere-cylinder and cone-column composite structures, combining the advantages of spherical hull, cone hull and cylindrical hull, which makes them have the characteristics of equal stress under uniform pressure, larger space occupancy rate and good hydrodynamic performance.

2.5.1 Sphere-Cylinder Composite Structure

Now sphere-cylinder composite structure is the most common structure of the submersibles. The below picture shows a streamlined pressure hull which consists of a column and two spheres (Fig. 23 “Deep Sea”). Usually the sphere-cylinder structural hull ensures the stability of the cylindrical hull by arranging a spiral rib plate (Figure 24 “beaver”). Besides, some sphere-cylinder structural hull is composed of a lot of concatenation spheres (Figure 25). This kind of pressure hull is a combination of the advantages of cylindrical and spherical structure, so it has a high strength and high space utilization.

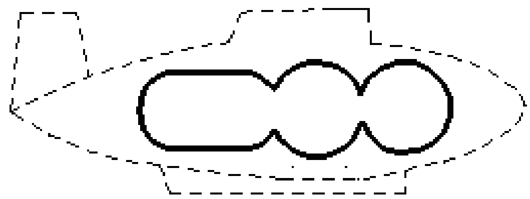

Figure 23
“Deep-Sea” Submersibles

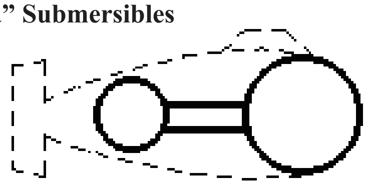

Figure 24
“Beaver” Submersible

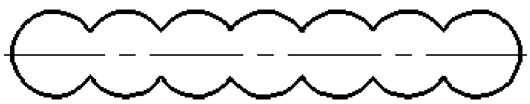

Figure 25
Composite Cylindrical Hull

2.5.2 Cone-Cylinder Structure

Pressure hull with cone-column structure is composed of a conical head and cylinder, such as “PC-4” submersible (shown in Figure 26). The “Qian die” submersible looks like a lentil. This kind of hull is not used widely because of complex calculation and difficult machinability.

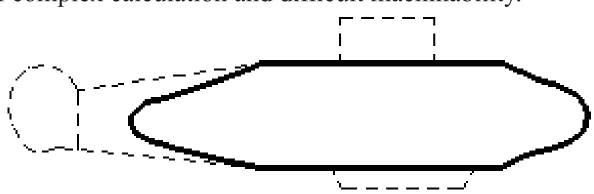

Figure 26
“PC - 4” Submersible

3. THE SELECTION OF THE MATERIAL IN THE PRESSURE HULL

Material used on the pressure hull is divided into two categories, metal and nonmetal. High-strength alloy steel is mostly used in the depth of more than 2000 meters. Mild steel or composite material is mostly used in the depth of 1000 meters. Reinforced plastic is mostly used in the depth of less than 1000 meters (Table 1). When choosing the material used in hull, metal corrosiveness, stress corrosion cracking, low cycle fatigue, metal creep, material brittleness and many other factors must be considered (Figure 27) (Fathallah, Qi, Tong & Helal1, 2014;Vinson, 1993).

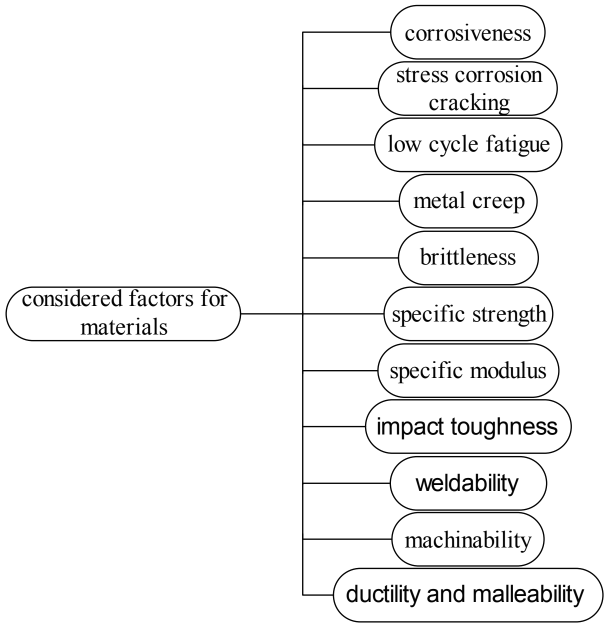

Figure 27
Considered Factors for Selecting Material

For the selected materials, the cost of making and the approach of obtaining have the same importance. Pressure hull's materials usually adopt steel, aluminum alloy, titanium alloy, reinforced plastic and so on (Figure 28).

Pressure hull mostly adopts steel. HY80, the most commonly used high strength steel, contains nickel, chromium, molybdenum and low carbon, so it has good ductility and toughness. Compared with the former, HY100 steel has greater yield strength and own the ability of withstanding repeated impaction, and avoids crack's expansion at low temperature. HY130 steel has good advantages on strength and toughness properties, but it is relatively difficultly manufactured for the large submersible manufacturing.

Titanium alloy has high strength, good corrosion resistance, available ductibility and so on, especially the resistance to compression and tension. However, its application is limited because of its high cost and complex manufacture process. With the further improvement of the mechanical properties of titanium alloy, machinability improvement and cost reduction, the titanium alloy will be widely used in pneumatic hull, containers, buoys and other submersible hulls.

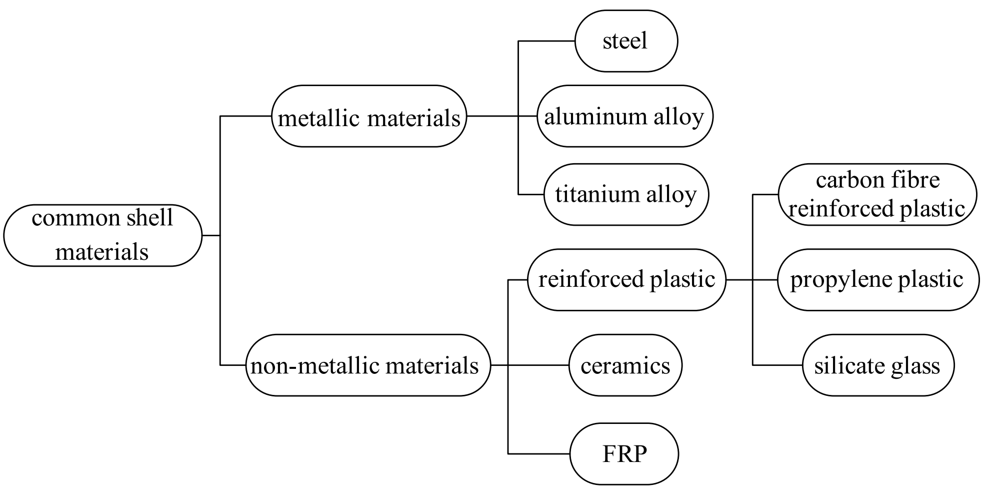

Figure 28
The Several Kinds of Common Hull Materials

The density of aluminum alloy is the three times as iron, and it has the characteristics of high strength and good plasticity. Superficial oxidation takes place on the aluminum rapidly, but the surface oxidation layer can inhibit its further oxidation. In addition, aluminum alloy still has the very high strength and ductibility at the low temperature. However, once the aluminum alloy cracking occurs, the structure is rapidly destroyed under the tiny energy. In addition, the cost of aluminum alloy is greatly higher than steel.

The reinforced plastic is widely used in submersibles, which works in the depth of less than 1000 meters. Especially, silicate glass, carbon fiber reinforced plastic, acrylic plastic and ceramic are promising materials, but because of the lack of robustness and connectivity with adjacent components, these materials are not widely used at present.

Table 1
The Form and Material of Typical Pressure Hull

the Name of the Submersible	Depth(m)	Material
Star- Ⅰ	60	A212B steel
Underwater Unmanned Submersible	60	Glass fiber reinforced plastic
Tiny Diver	75	A-36 welded steel
AUV	180	plastic
Kuroshio- Ⅱ	200	Low carbon steel （SM-41）
Nekton -A	300	Low carbon steel
PC-14	360	A516(70) steel
SP-350	400	Forging steel
Deep-sea	600	High strength structural steels
Castor Fiber	600	HY-100
Star-Ⅲ	610	HY-100
Benthic Rover	1000	Polypropylene plastic
DS RV- Ⅰ	1050	HY-140
Dark Star -4000	1200	HY-SO
DS RV- Ⅱ	1500	HY-140
Submersible Shinkai-6500	2000	NS90 steel
Deep Investigation	2400	(18% nickel) 200 KSI alloy steel
Alvin	3600	Titanium alloy 621.08
Aluminant	4500	Aluminum alloy （7079-T6）
Nautile	6000	Titanium alloy
Dark Star-2000	6100	HY-140
Archimedes	11000	Nickel - chromium - molybdenum forging steel

CONCLUSION

The overview of the structural design and the material selection concerning submersible pressure hull was summarized. Overall, the merits of submersible structure are evaluated from four aspects of buoyancy coefficient, the structure strength, the internal space occupancy rate and water resistance. The primary indicators, evaluating the operation level and flexibility of the submersible, are the internal space occupancy rate and water resistance. Besides, material selection criteria of pressure hull should pay attention to the superior mechanical properties and chemical properties, such as high strength and corrosion resistance and so on.

For the existing various hulls, the shortcomings still exist. Such as, stress concentration and the low space occupancy rate. Therefore, the study of a new type of hull structure is still very urgent. Furthermore, the new materials of pressure hull should focus on combining the advantages of metal and nonmetal, which could ensure the submersible to work long underwater, and provide important support for the design of deep-sea submersibles.

REFERENCES

Blachut, J., & Smith, P. (2008). Buckling of multisegment underwater pressure hull. *Ocean Engineering, 35,* 247-260.

Blachut, J, & Jaiswal, O. R. (2000). On buckling of toroidal hulls under external pressure. *Computer & Structures, 77,* 233-51.

Blachut, J. (2004). Buckling and first ply failure of composite toroidal pressure hull. *Computers and Structures, 82,* 1981-1992.

Burcher, R., & Rydill, L. (1994). Concepts in submarine design. Cambridge University Press.

Cheng, Y. X. (2012). *Structural optimization design of the pressure hull based on non-uniform ring-frames theory*. Harbin, China: Harbin Engineering University.

Fan, X. D. (2008). *Design and analysis of carrier for ocean-exploration AUV*. Harbin, China: Harbin Engineering University..

Fathallah, E., Qi, H., Tong, L. L., & Helal, M. (2014). Design optimization of composite elliptical deep-submersible pressure hull for minimizing the buoyancy factor. *Hindawi publisliing corporation advances in meclianical engineering*. Retrieved from http://dx.doi.org/10.1155/2014/987903.

Fathallah, E., Qi, H., Tong, L. L., & Helall, M. (2014). *Design optimization of composite elliptical deep-submersible pressure hull for minimizing the buoyancy factor*. Retrieved from http://dx.doi.org/10.1155/2014/987903.

Liang, X. X. (2006). *Structural study on design of deep-sea submarine pressure hull.* Harbin, China: Harbin Engineering University.

Liang, C. C., & Chen, H. W. (2004). Optimum design of multiple intersecting spheres deep-submerged pressure hull. *Ocean Engineering, 31,* 177-199.

Ma, L. (2012). *Conceptual design of 1000-meter light operating manned submersible*. Harbin: Harbin Engineering University.

Ma, L., & Cui, W. C. (2005). Path following control of a deep-sea manned submersible based upon NTSM. *China Ocean Engineering, 19*(4), 625-636.

Ma, L., & Cui, W. C. (2004). Simulation of dive motion of a deep manned submersible. *Journal of Ship Mechanics, 8*(3), 54-59.

MacKay, J. R. (2012). *Department of precision and microsystems engineering on lightweight design of submarine pressure hulls*. Delft: Delft University of Technology.

Ness, C. C., & Simpson, W. (2000). A new submarine paradigm. *Naval Engineers Journal, 112*(4), 143-151.

Pan, T. (2010). *Structural strength analysis and optimum design of deep-sea submersible*. Harbin, China: Harbin Engineering University.

Qu, W. X. (2012). *Structural Design and Analysis of Pressure Hull in Manned Submersible*. Harbin: Harbin Engineering University.

Reynolds, T., Lomacky, O., & Krenzke, M. (1973). Design and analysis of small submersible pressure hulls. *Computers and Structures,* (3), 1125–1143.

Shi, D. P., & Li, C.C. (1991). S*tructural Strength of Submersible*. China: Shanghai Jiao Tong University Press.

Vinson, J. R. (1993). *The behavior of hulls composed of isotropic and composite materials*. USA : Springer Netherlands.

Xie, Z. S., & Wang, Z. L., & Wu, J. G. (2004). *Structural Analysis of Submarine*. Wuhan, China: Hua Zhong University of Science & Technology Press.

Zhang, W., Zhang, . K., & Cui, W. C. (2000). Structural research on reliability of submarine cylindrical pressure hull. *ShipBuilding of China, 41*(4), 35-39.

Zhu, J. M. (1992). *The design of submersible.* China: Shanghai Jiao Tong University Press.

Zhu, G. F., & Wu, J. G. (2002). *Structural analysis of failure mode and effect of submarine*. Ship Engineering.

