Application Status and Research Progress of Resin Matrix Composites in Unmanned Underwater Vehicle

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Abstract. Unmanned underwater vehicle (UUV) is a kind of underwater unmanned vehicle. In recent years, it has been widely used in civil and military fields. With the development of the unmanned underwater vehicle to multi-function, strong concealment, high performance and other directions, different kinds of resin matrix composite materials with excellent sound absorption, corrosion resistance, high specific strength characteristics, the utilization rate of unmanned underwater vehicle gradually increased and has broad development potential. In this paper, the application status and key technologies of resin-matrix composites in the field of unmanned aerial vehicle (UAV) are studied from two aspects of function and structure, and the technical trend of resin-matrix composites in the future UUV is described, and its development prospect is forecasted.

1. Introduction

As a new type of underwater unmanned system, unmanned underwater vehicle has become the focus of the development of underwater weapons in the world due to its characteristics of high autonomy, low risk, strong concealment, and flexible deployment. For example, the US Navy has developed seahorses, Large Diameter Innovative Principle Prototype (LDUUV-INP), and other underwater vehicles for a parallel installation. Russia takes Poseidon as an important node to its nuclear force. At present, with the progress and development of unmanned systems, unmanned aerial vehicles (UAVs) show a variety of application trends such as intelligence, remote communication networking, covert navigation, etc. These characteristics also put forward higher requirements for the selection of materials and manufacturing technology of UAVs. Resin matrix composite has been widely used in the unmanned aerial vehicle (UAV) due to its advantages of designability, high specific strength, sound absorption, wave penetration, and other functional characteristics, and has gradually replaced the conventional metal components, which has a broad development prospect. In this paper, the application status of resin matrix composites in the underwater vehicle is analyzed and studied, which provides a reference for the development trend of resin matrix composites in the future.
2. Application status of resin matrix composites in underwater vehicles

Resin matrix composite material has the characteristics of high specific strength, strong design ability, seawater corrosion resistance, non-magnetic, lightweight, and so on, playing an important role in the field of underwater equipment, foreign submarine sonar dome, command room enclosure Shell, superstructure, lifting mast, rudder wing, propeller and other parts of the application\textsuperscript{1}. It has been proved by practice that it has an obvious effect on enhancing the submarine's payload capability, reducing the lifetime cost, and enhancing stealth performance. UUV is generally composed of a skeleton, buoyancy device, propulsion system, control system, and detection system, etc. The material system composed of these components plays an important role in a complex and diverse working environment. Among them, resin matrix composites as functional materials or structural parts have been widely used in various parts of the unmanned underwater vehicle.

2.1. Corrosion resistance

The pressure cabin structure is the overall carrying structure of the submersible, mainly carrying the battery and the control system of the submersible. At the same time, the pressure cabin is also the connecting segment between the frames, which needs to meet the overall stiffness requirements of the submersible hoisting. In the ocean salinity and humidity are higher, and there are more marine micro-organisms, so the main pressure chamber structure of the knot the corrosion resistance of structural materials is extremely high. Other materials such as wood and steel materials, the former long in the sea decomposition occur in oceanic environments, and the latter rust under the influence of oceanic factors. In contrast to a resin base, the composite material has good corrosion resistance in the Marine environment and can meet the design requirements of the pressure tank.

Shi etc.\textsuperscript{2} conducted ultrasonic processing of hexagonal boron nitride (H-BN) powder in polyethyleneimine (PEI) aqueous solution After modification, the corrosion resistance and toughness of the resin base material were significantly enhanced. The dispersing process is complex and costly. Loan etc.\textsuperscript{3} modified polyaniline/carbon nanotube hybrid by ionic liquid. The results show that the mechanical properties of the resin base material are improved greatly after modification, but the ion is used The liquid modification process is too complicated and has low operability. Jing et al.\textsuperscript{4} modified by hybrid nano molybdenum disulfide Resin- based materials, it was found that the modified epoxy resin-based heavy anticorrosive materials have long-term corrosion resistance, but the method of complex deletion of the content: results Miscellaneous and costly.

Saliba\textsuperscript{5} proposed that the combination of nano-level inorganic components and resin base dramatically increases the interface area, giving polymer nanocomposites superior performance. Ming et al.\textsuperscript{6} successfully prepared a robust underwater superhydrophobic material (HN/ER) by using MPS (Methacryloxy propyl trimethoxysilane) -SiO$_2$/PNIPAM (N-isopropyl acrylamide) hybrid nanoparticles and epoxy resin (ER). SiO$_2$/PNIPAM hybrid nanoparticles can improve the multi-scale roughness of the coating and have excellent wear resistance. Epoxy resin can be used as the intermediate layer between hybrid nanoparticles and the matrix to improve the corrosion resistance of the material. The HN/ER has excellent underwater superhydrophobic properties and shows high stability in harsh environments, including acid and alkaline, strong ionic strength, and mechanical wear. In addition, due to the presence of the high-density PNIPAM polymer, the material can also protect the substrate in corrosion solutions against bacterial attachment and subsequent biofilm formation.

Additionally, due to the corrosive nature of the Marine environment, resin-based composites have a significant advantage over conventional welded or bolted steel casing repair for structural repair.

George et al.\textsuperscript{7} verified the feasibility of resin matrix composite repair technology and fiber-reinforced polymer (FRP) repair method by using finite element analysis and related models. It is proved that the ultimate strength of the specimens repaired by resin matrix composites is significantly improved and the member matching integrity is stronger than that after corrosion. Through the evaluation of load-displacement parameters, energy absorption, ductility, and strain values, it is also shown that the effect of underwater repair is very similar to that of traditional air repair. Therefore, it has a certain reference value for future underwater repair projects.
Zhao Yu [8] took epoxy resin as the base and added fluoro silane to modified kaolin and tetrafluoroethylene to obtain superhydrophobic composite materials, which greatly accelerated the corrosion resistance and service life of the materials. In addition, secondary spraying and adding gaseous silica as a thixotropic agent [9] enable resin matrix composites to have superior mechanical durability and anti-icing. In practical application, it is found that although the production technology of composite material is flawless, there are still some defects. The surface state of the material directly influences the corrosion resistance of the material, and the material with exposed or cracked ends is easier to destroy. Therefore, the addition of carbon fiber as the reinforcing agent can improve the characteristics of the submersible pressure chamber to a certain extent.

Yijun Fan etc.[10] took samples of carbon fiber resin matrix composites soaked in simulated seawater at 85℃ for different days and tested them for non-notched impact strength, as shown in Figure 1A. The samples of carbon fiber resin matrix composites treated in an oven at 100℃ for different days were taken out for a non-notchable impact strength test, and the influence of heat-resistant oxygen aging time on impact strength was characterized. The results are shown in Figure 1B. Samples of carbon fiber resin matrix composites treated for different days in a salt spray aging tank at 35℃ were taken out for a non-notch impact strength test to characterize the influence of salt spray aging time on impact strength. The results are shown in Figure 1C. As can be seen from the figures, the impact strength of carbon fiber reinforced resin base material has been maintained at a high level, and with the extension of time, the declining trend is slow, and the corrosion resistance of carbon fiber reinforced resin base material is optimal in the adverse service environment.

Fig. 1 Influence of extreme environmental action time on impact strength of carbon fiber reinforced resin matrix composites.
(a) Seawater immersion (b) Thermal oxygen aging (c) Salt spray aging

2.2. Sound permeability
The sonar equipped with UUV undertakes various tasks of seabed mapping, navigation, and communication.
As a sonar protection device, the resin matrix composite material and acoustic permeable rubber cover \cite{11} can meet the requirements of low magnetic and acoustic permeability.

For example, adding polydimethylsiloxane (PDMS) and the mixture of titanium dioxide particles \cite{12} on modification of carbon fiber reinforced resin matrix composites layer structure, and the urea reinforced polyurethane rubber sealing material \cite{13} have the same longitudinal acoustic impedance with water, a combination of sonar dome has good low and high-frequency acoustic attenuation performance.

The sonar fairing made of resin matrix composite material has an obvious inhibition effect on the flow-induced load of the underwater vehicle at high speed. Compared with traditional materials, each fair has exceptional performance, as shown in Table 1.

| Material Category          | Advantage                          | Disadvantage                           |
|----------------------------|------------------------------------|----------------------------------------|
| Metal                      |                                    | Low sound transmission efficiency, high cost |
| Alloy Steel Plate          | Excellent seawater resistance       | Installation and manufacturing difficulties, low yield |
| Titanium Alloy             | High specific strength              |                                        |
| Rubber                     | Sound impedance and seawater close  | There are bubbles between the inner and conforming layers, resulting in stratification |
|                            | Good sealing waterproof            |                                        |
| Resin Matrix Composite     | Seawater aging resistance           |                                        |
|                            | Low construction cost              |                                        |
|                            | Strong vibration absorption         |                                        |

2.3. Wave absorption

The acoustic stealth ability of UUV is an important index to evaluate its combat effectiveness. The traditional method is to cover the surface of the shell with acoustic stealth material, which easily falls off and affects the navigation flexibility, and the defect of high cost is gradually eliminated. Fiber-reinforced composite and polyurethane resin sound-absorbing material are used to fabricate the stabilizer and rudder surface, which has good stealth effects. Its stealth effect is mainly reflected in the following three aspects: First, the sandwich structure \cite{14} has a good sound shielding effect. The D-type support, formed by the polyurethane resin sound absorbing material in the middle and the fiber composite material on the surface, expands the compliance coefficient of the vertical surface, achieves vibration attenuation while avoiding the outward radiation of the internal noise of the structure, and reduces the acoustic target intensity of the structure, as shown in Figure 2. Second, compared with steel, the sandwich composite material has larger structural damping, which greatly reduces the vibration level. See Figure 3 and Figure 4 for details. Three is a polyurethane resin water sound absorption material that can reduce the magnetic signal. Polyurethane resin sound absorbing material has the characteristics of high damping coefficient, strong water resistance, strong designability, and excellent adhesion. Using the mechanism of viscoelastic damping and sound absorption, for an ideal elastic solid, the stress and strain are always in the same phase, and the energy is stored in the form of elastic potential energy, and then all converted into kinetic energy without loss. When the sound wave is transmitted to the surface of polyurethane material, the phase difference between strain and stress is generated in the polymer under the action of alternating stress, and the molecular chain is distorted and deformed, and then internal friction occurs \cite{15}, which converts sound energy into heat energy consumption and achieves the effect of attenuating magnetic signals.
In addition, the combination of polyurethane resin material and barium titanate, flexible polyurethane sandwich structure, and bamboo leaf particles all have the advantages of the wide range of sound absorption frequency and good compressive strength, which can be widely used to make the acoustic stealth structure of underwater vehicle [16-18]. Yu et al. [19] constructed a new type of metal hollow sphere/polyurethane (MHSP) acoustic composite by casting method using 316L stainless steel hollow sphere (316L HS) and polyurethane (PU) resin as materials. Although polyurethane resins have been used in the field of acoustic materials, their application is limited by the inhomogeneity of pore size and distribution. The hollow metal sphere developed in recent years is a kind of cavity material with relatively controllable size and distribution, which can solve the above shortcomings. The acoustic experiment results of the composite show that compared with the monolithic PU, the acoustic transmission loss of the composite increases with the change of acoustic impedance and resonant frequency, and the maximum acoustic absorption peak moves to a lower frequency. The surface of hollow metal spheres in the MHSP composite was modified by a silane coupling agent, and the sound insulation performance of the MHSP composite was further improved.
2.4. Structural characteristics of resin matrix composites

To adapt to the deep-sea high-pressure environment, the thickness of the skeleton and pressure cabin plate of the UNMANNED underwater vehicle is also increasing, which easily leads to the increase of the weight of the equipment and affects the distribution of the center of gravity and buoyancy center. To ensure the stability and other basic performance of the deep-sea UUV, it is necessary to control the overall weight of the UUV to improve its comprehensive performance. Resin matrix composite material has the characteristics of low density, which can effectively increase the buoyancy and payload of underwater vehicle, save energy, and improve the economic benefits of navigation or combat. Using carbon fiber sandwich resin matrix composite material to make submarine mast, instead of metal tube, achieve weight reduction effect of more than 65%. In addition, the control surface of deep-sea UUV made of resin-based material with foam core reduces the weight of tail and has better underwater dynamic performance.

Resin matrix composites have the properties of material-structure unity, which reduces the degree of defects and cracks in the process of connection and assembly, improves the production speed, and shortens the manufacturing cycle. At home and abroad, the research in the field of resin matrix composites has changed from laminated plate combined with the reinforced structure to the material-structure integrated sandwich structure. From different materials to solve weight loss, corrosion resistance, and other problems, the development of multi-functional composite manufacturing.

Currently, the connection modes of resin matrix composite materials in underwater vehicles are mostly mechanical connection, adhesive (bonding connection), and mixed connection [20]. Although the traditional connection technology has some advantages such as high structural strength, easy maintenance, and good impact resistance, it is easy to have problems in the complex environment of the underwater vehicle due to its low connection efficiency. Due to the lack of thickness direction change, the effect of traditional cementing solidified composite is not good. The effect of interlayer connection is an important factor affecting the quality of the structure. The low damage tolerance of sandwich structure under impact load can be solved by using Z-PIN reinforced resin matrix composites. Low energy impact loads lead to the mechanical strength of sandwich composites reduced defects. Gaye Kaya et al. [21] proposed that the damage of the panel could be eliminated by z-PIN reinforcement of the core part of the sandwich structure. The impact tests were carried out at different energy levels (20 ~ 50 J). The addition of Z-axis nails reduced the elasticity and ductility of the composite but increased the stiffness of the composite. Z-pin reinforcement increases the peak force but decreases the peak deformation. Based on the study of Dong Xiaoyang et al. [22], it is concluded that z-PIN connection is affected by multiple directions, such as volume fraction, implantation Angle, and diameter, as shown in Table 2. In the actual design of an underwater vehicle, it should be processed according to different mission scenarios of the underwater vehicle to maximize its combat effectiveness.

| Implant Angle | Criteria | Performance Characteristics |
|---------------|----------|-----------------------------|
| Implant at a 90 degree Angle | Z - pin diameter of 0.5 mm Volume fraction 0-3.0% | The strength of single lap joint increases linearly with the increase of Z-pin volume fraction |
| | Z - pin diameter of 0.5 mm The z-PIN volume fraction is 1.5%, | The forward cutting strength of Z-pin joint is 16.76mpa |
| | Z - pin diameter of 0.5 mm Volume fraction 0-3.0% | The strength of the joint is 33.2% higher than that of the joint without Z-pin |
| | Z - pin diameter of 0.5 mm Volume fraction 0-3.0% | With the increase of Z-pin placement Angle, the strength of the single lap joint first increases and then decreases |
| Implant at a 40 degree Angle | Z - pin diameter of 0.5 mm Volume fraction 0-3.0% | The maximum shear strength was 21.04Mpa |
3. Future trends of resin matrix composites for underwater vehicles

3.1. Intelligent structure design improves material strain performance
Resin-based materials have good self-inductive functional characteristics, and their resistance will change with the change of strain, that is, there is a strain-electrical resistance sensitivity effect. By analyzing the bearing performance and self-inductive characteristics of resin-based composite materials, an intelligent prestressed structure system of underwater vehicles can be constructed [23].

The problem of path planning refers to finding an optimal path for UUV to reach the target point safely according to certain evaluation criteria (least energy consumption, shortest route, least time, etc.) in the operating environment of the vehicle.

Therefore, obstacle avoidance must be considered in this kind of problem. The sensor telemetry network of the underwater vehicle is established by installing multiple sensors inside the surface material of the underwater vehicle. Not only can the ant colony algorithm and dynamic algorithm be combined to find the shortest path of UUV [24] to achieve optimal obstacle avoidance, but also the stress and damage characteristics of surface materials of UUV can be tracked, monitored, and prevented. In this way, online real-time health monitoring of the field of the surface structure of the submersible is realized [25].

3.2. Improve cold/heat resistance and expand application scenarios
Due to different working objectives, the components of UUV are in complex high or low-temperature environments. So silent hunter on design and development of resin matrix composites attention should be paid to the improvement of the performance of the cold/hot resistance, summer rain [26] proposed an integration such as resin-based thermal protection structures, as shown in figure 5, using high-temperature resistant polyimide composites and gel fiber felt composite structure, can give full play to the advantages of various kinds of materials, completely coupled with the use of the thermodynamic device.

![Fig. 5 Integrated resin base thermal protection structure and some mechanical properties](image)

3.3. Increase the progress of integrated research and development and improve the level of automatic manufacturing
The initial resin matrix composite molding technology was autoclave molding technology with preparatory manual placement [27]. The equipment has defects in high energy consumption and a large investment. In 2016, the proportion of automatic manufacturing of composite components reached 50%. The hand-pasting process characterized by high labor intensity, poor process control, and severe pollution has disappeared, and the labor-intensive hand-pasting process has also been reduced to 30% [28]. By combining autoclave molding technology with automation, laser positioning and automatic cutting of preparatory material are carried out, which greatly improves the quality of resin matrix composite components. Its technological parameters are shown in Figure 6, and its technological properties after curing are shown in Table 3.
Fig. 6 Treatment process of autoclave cured resin composites [27]

Table 3 Mechanical properties of autoclave cured specimens

|                         | Tensile Strength/MPa | Compressive Strength/MPa | Bending Strength/MPa | Interlaminar Shear Strength/MPa |
|-------------------------|-----------------------|--------------------------|----------------------|-------------------------------|
| Average                 | 2300                  | 1050                     | 1650                 | 95                            |
| Minimum                 | 2100                  | 850                      | 1450                 | 85                            |

At present, the automatic coverage of composite materials abroad has reached about 70%, while China's automatic manufacturing is still in its infancy, and there are many ongoing engineering verifications. At the same time, with the increasing proportion of resin matrix composite materials in the submersible, to adapt to the development trend of large, complex, and integrated components, the first is the need to get away from manual automatic laying technology and comprehensive winding technology research; The second is the research on the automation of the parts in the submersible, and the promotion of the flexible automatic assembly technology and automatic detection technology of the materials.

4. Conclusion
With the continuous upgrading of UUV, the new complex service environment puts forward higher requirements for the material system used in UUV. Resin matrix composite material because of its excellent oneness and can design, structure, function and gives the functional characteristics of a variety of resin matrix, not only can be used as a part of the unmanned coupled structure, used to lose weight, save cost, also can use acoustic stealth, corrosion resistance and acoustic characteristics which implement the overall performance of ascension. With the continuous improvement of connection technology, UUV can greatly reduce the production cycle and improve the carrying capacity. At present, resin matrix composites have been applied to various types of unmanned underwater vehicles, but there are still some shortcomings of resin matrix composites, such as complex preparation processes and poor heat resistance. It is necessary to further improve the preparation automation level, improve the temperature resistance of the matrix and broaden the application scenarios.

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