

Advances in Material Design and Functional Integration for Soft Robotics

Yahao Su

{202315020219@sust.edu.cn}

Ulster College, Shaanxi University of Science & Technology, Xi'an, Shanxi, China

Abstract. In recent years, soft robots have shown irreplaceable development prospects in underwater, medical and industrial fields with excellent human-computer interaction and adaptability to complex environments. Materials, as the core of its function realization, directly determine the perception, driving performance and service life. At present, the research on soft robot materials has made multi-dimensional progress: the material system covers elastomer, polymer and intelligent composite materials, and the preparation technology is dominated by 3D printing fused deposition modeling (FDM), stereo lithography apparatus (SLA), supplemented by composite lamination and textile weaving technology. Therefore, through the analysis of the preparation technology, core classification and adaptability of different scenes of soft robot materials, combined with the material performance data, this paper systematically combs its research status and application cases, and finds that the current materials are mature in structure, drive and function, but the mechanical properties still need to be optimized. Finally, the paper explores the emerging materials, and puts forward its own opinions and Prospects on how to better combine the emerging materials with machinery.

Keywords: Soft Robot, 3D Printing, Dual Wave Co Curing, Intelligent Materials, Scene Adaptability.

1 Introduction

In recent years, driven by global scientific and technological innovation, the research and development of new materials has made breakthroughs, and the deep integration of mechanical manufacturing and artificial intelligence has further spawned the frontier field of soft robots. Compared with traditional robots, soft robots have strong human-computer interaction, can adapt to more complex environments, and have good flexibility, ductility and compatibility. It has irreplaceable development prospects in underwater, medical, industrial and other fields. Materials are the basis for the realization of soft robot functions. The perception performance, human-computer interaction, driving performance and even service life of soft robot are directly determined by the performance of its core materials. Therefore, the research on the material application of soft robot has become the key to promote the technological breakthrough in this field.

At present, the research on soft robot materials has formed a multi-dimensional development pattern: on the one hand, researchers realize the two-dimensional to three-dimensional shape transformation of materials under programming control by introducing patterning or orientation alignment structure, and such deformation can be accurately predicted by finite element analysis (FEA) [1]; On the other hand, the material system has been continuously enriched, covering the direction of elastomer, polymer, intelligent polymer and composite multifunctional materials, and has made phased achievements in optimizing the response speed of driving materials and improving the sensitivity of sensing materials. But at the same time, it also faces a series of challenges, such as "the single material can not meet the needs of multi-functional integration", "some materials have poor durability, heat resistance and other properties", "large-scale preparation costs are high", and so on. In view of this, this paper systematically reviews the preparation technology of various materials used in soft robot in recent years, the classification of core materials, and the adaptability of materials in different scenes, and explains its research status and application cases one by one. Finally, combined with the research and development trend of emerging materials, the path of deep integration in the fields of materials science, mechanical engineering and artificial intelligence is prospected, which should be guided by the core requirements of flexible driving and load adaptation of soft robots, and the emerging flexible intelligent materials should be deeply coupled with the design of bionic mechanical structures. At the same time, the key research directions of future soft robot materials are clarified, which can provide reference for innovation in related fields.

2 Material Preparation Technology in Soft Robot Development

The preparation of soft robots is closely related to materials. At present, the research community mostly adopts 3D printing method. In addition, there are some special technologies such as multifunctional composite lamination technology, textile and functional weaving technology. The core of this part is to classify the material preparation technology into two categories -3D printing technology and other technologies.

2.1 3D Printing Technology

3D printing technology, also known as additive manufacturing, is the most promising soft robot preparation technology because of its fast forming speed. Compared with traditional technology, 3D printing can produce complex geometry, realize personalized customization and small batch production. According to different principles and materials, 3D printing technology is mainly divided into two forms: Fused Deposition Modeling (FDM) and stereo lithography apparatus (SLA). FDM is formed on the printing platform by heating and melting thermoplastic materials, such as PLA and ABS, through the nozzle [2]. This is the most common form and printing process of 3D printing, as shown in Figure 1. Because of its high cost performance and easy to use, it is welcomed by many research teams.

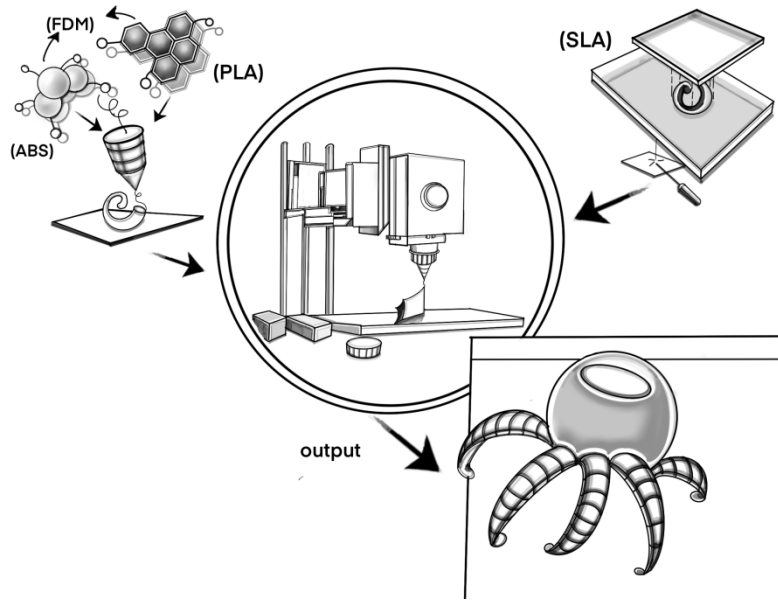


Fig. 1. Common forms of 3D printing and printing process diagram (Picture credit: Original)

Modeling and Design Stage. Different from the traditional "design the structure first and then select the material", the soft robot needs to define the elastic modulus of the material first. For example, the medical robot needs $e \leq 1\text{MPa}$ to match the human tissue and drive response range. For example, the temperature driven material needs to define the deformation temperature range before designing the structure. Two kinds of design methods are emphasized here.

The first is bionic structure design, which solves the strength, performance and other problems in product design through the structure of organisms. The composite cold field 3D printing technology developed by the team of China University of science and technology maintains the high viscosity of ink through 5°C low temperature environment, and combines with the highly directional arrangement of liquid crystal units induced by shear force to prepare liquid crystal elastomers (nat-lces) with near ambient temperature response characteristics. Its orientation order parameter is more than 30 times higher than that of the traditional method, which can realize the reversible deformation of complex structures such as saddle shape and cone shape, and is suitable for the flexible sensor parts of wearable devices such as smart wristbands [3]. This result reflects the collaborative optimization mechanism of material and structure in mechanical properties and response behavior.

Multi material collaborative design refers to the optimal combination and integrated design of a variety of materials with different properties according to the functional requirements of products, so as to achieve the comprehensive performance that a single material cannot achieve. The University of Texas team developed a hybrid epoxy acrylate resin. Multi material integrated molding is realized by wavelength curing mechanism. Among them, 365 nm UV light drives the rapid polymerization of epoxy groups to form a rigid skeleton, while 405 nm UV light triggers the crosslinking of acrylate segments to form a highly elastic matrix [4]. This dual

wavelength co curing technology can achieve precise control and spatial distribution of hard and soft materials in a single print by adjusting the light intensity ratio. This precision level is expected to promote the development of applications such as soft robots, sealants, prosthetics and wearable health monitors.

Establishment of Printing System and Post Printing Processing. When establishing the printing system, it is necessary to adjust the corresponding parameters to make the system run stably. Different 3D printing technologies have different adaptation scenarios. Melt deposition molding (FDM) is suitable for thermoplastic elastomer, such as TPU, digital light processing (DLP) is suitable for high-precision photosensitive elastomer, such as PDMS based resin, and direct ink writing (DIW) is suitable for high viscosity functional ink, such as carbon nanotubes/silicone rubber composite ink.

Post processing is mainly divided into two parts: performance enhancement and defect repair. Performance enhancement can be divided into curing treatment and surface modification. For example, the team of Tianjin University of science and technology used the FDM hot bed to heat cure the material after printing the magnetic control soft robot [5]. For defect repair, common defects such as interlayer peeling, bubbles, etc. These will have a certain impact on the research results. The common solutions are to use ultrasonic vibration to eliminate bubbles and coating adhesive on the interface to improve the adhesion between layers.

2.2 Other Preparation Technologies

In the field of manufacturing flexible intelligent components, multi-functional composite lamination technology and textile and functional weaving technology are two core paths, both of which have their own technical characteristics and jointly serve the R&D needs of flexible intelligent devices.

Firstly, the multifunctional composite lamination technology is introduced. Its principle is to stack different functional layers, such as driving layer: shape memory polymer, sensing layer: conductive hydrogel, and structural layer: high-strength aramid fiber membrane, into an integrated component through "layer by layer composite+interface combination". This technology also has a wide range of applications. The Peking University team has developed a soft robot with an outer layer of carbon fiber reinforced epoxy resin with a modulus of 10GPa and a thickness of 200 μ m, an inner layer of dielectric elastomer with a modulus of 1MPa and a thickness of 100 μ m, which can withstand 2MPa water pressure and achieve 10% strain by vacuum hot pressing at 80 $^{\circ}$ C and 2MPa [6]. This provides a new tool for biological interaction research. However, the process is complex and the preparation is difficult, so this technology is still in the optimization stage.

Different from the "stacking logic" of lamination technology, textile and functional weaving technology takes textile fibers as the matrix, composites functional materials into fibers, and then makes flexible fabric substrates through the knitting/knitting process. Different fiber types are selected for different purposes. For example, silver coated copper fibers in conductive fibers are mostly used in medical rehabilitation equipment and glass fibers in high-temperature resistant fibers. The temperature resistance is more than 200 $^{\circ}$ C, which is suitable for industrial scenes. The team of Jiangnan University weaves spandex core spun yarn on a spinning frame and assembles it on a soft robot through a series of cutting and sewing to realize the construction of a textile based bending soft robot [7]. This material has high permeability, high ductility, and

is suitable for large-scale production. But at the same time, the accuracy is low, and the functional fibers are easy to break in weaving.

3 Core Materials of Soft Robot

The 3D printing mentioned in the previous chapter includes fdm/sla, dual wavelength co curing, composite lamination, textile weaving and other preparation technologies, which need to rely on the characteristics of specific material system to achieve process landing and performance optimization.

3.1 Elastomer Materials

Elastomer materials are widely used in the field of soft robots, including silicone rubber and polyurethane [8]. Its core advantage lies in its excellent elasticity, plasticity, high flexibility and deformation ability, which plays a key role in the driving unit and structural support of soft robots. In terms of classification, elastomer materials can be roughly divided into thermoplastic elastomer and thermosetting elastomer. Silicone rubber belongs to thermosetting elastomer, while polyurethane (TPU) belongs to thermoplastic elastomer. Both are important research objects in the field of soft robot.

Silicone rubber is a typical type in the field of soft robot [9]. Silicon based elastomer has become a classic choice for soft robot due to its low modulus and high ductility. Its research focus is on surface modification and functional filler composite to improve interface adhesion and multi-function integration ability. At present, the scientific research team has developed a new barrel photopolymerization (VP) three-dimensional (3D) printing silicone rubber (SR) ink [10], which greatly improves the disadvantage of low mechanical strength and fatigue resistance of silicone rubber. The team of Bristol University found that the applicability of silicone rubber as artificial muscle was proved through its variable stiffness behavior, [11] which provides a reference for the production of humanoid robot and human-computer interaction.

TPU as the representative thermoplastic elastomer has the core advantages of easy processing and recyclability, and the development of 3D printing technology has further promoted its large-scale application in soft robot. The research of Peking University team shows that: through the TPU double-sided coated nylon woven fabric, combined with the laser cutting and 3D printing thermal bonding process, a soft operating arm with a contraction ratio of 2941% is prepared, and its end gripper can realize multimodal movement, which can meet the requirements of grasping objects with different shapes [12]. The material also has the defect of easy softening at high temperature. When the ambient temperature exceeds the glass transition temperature, the mechanical properties will be significantly reduced, which limits its application in industrial high-temperature detection, engine compartment operation and other scenarios. In the future, the thermal stability needs to be improved by molecular chain modification or high-temperature resistant filler composite.

3.2 Polymer Materials

Polymer materials focus on the integration of driving and sensing of soft robot with the core of functional characteristics such as electrical activity and thermal response. Current research focuses on breakthroughs in key indicators such as low voltage drive and high response speed.

Typical materials include dielectric elastomer, relaxor ferroelectric polymer and liquid crystal elastomer.

Dielectric elastomer is a typical electroactive polymer. Its driving principle is based on the dielectric expansion effect under the action of electric field. The core of research is to reduce the driving voltage and improve the energy density through material molecular design. The research of Tsinghua University team has made an important breakthrough: the polar fluorinated polyacrylate developed has achieved a movement speed of 20.6 bl/s at a low voltage of 400 V, with an energy density of 154 w/kg, which is far higher than the traditional acrylate de[13]. Through the design of dynamic physical crosslinking network, the team solved the potential safety hazard of traditional de requiring high driving electric field, laying the foundation for its application in near human scenes. In the application scenario, the high energy density of dielectric elastomer makes it suitable for bionic fast mobile robots. As shown in Figure 2, the biped jumping robot can simulate the rapid contraction of biological muscles. The main challenge at present is that the pre stretching process will limit the driving performance. In the future, people need to reduce the dependence on pre stretching and realize more flexible structural integration.

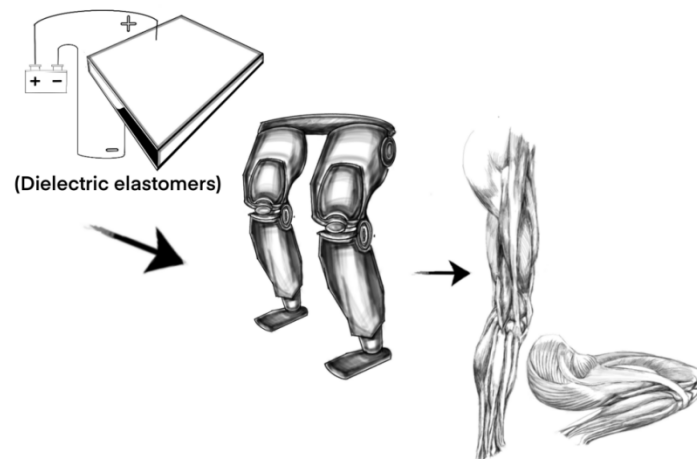


Fig. 2. Schematic diagram of biped jumping robot (Picture credit: Original)

Relaxor ferroelectric polymers have the advantages of low driving voltage and high stability. The research focus is to optimize the ferroelectric domain structure through chemical modification and improve the electrical deformation performance. The team of southwestjiaotonguniversity prepared P (VDF TrFE cfe-fa) polymer with small domain structure by introducing fluoroacrylic acid (FA) units into P (VDF TrFE CFE). The bending angle under $10 \text{ v}/\mu\text{M}$ electric field reached five times that of commercial PVDF. The movement speed of biped soft robot based on this material reached 19 bl/s, which was close to the movement efficiency of biological muscle [14]. The low-voltage driving characteristics of this kind of material make it suitable for wireless driving scenarios. The crawling and detection actions of the robot can be controlled only through low-voltage wireless signals, which improves the safety of operation.

Liquid crystal elastomer is a typical thermal responsive polymer, which has both the orientation order of liquid crystal and the deformation ability of elastomer. The LCE doped with carbon nanotubes developed by the team of Sichuan university can achieve a strain rate of 480%/s at 30 ° C body temperature [15] through the photothermal conversion effect of carbon nanotubes and the orientation control of liquid crystal molecules. The autonomous crawling robot based on this material can complete accurate movement driven by human body temperature. At the application level, the thermal response characteristics of liquid crystal elastomer make it have unique advantages in biomedicine and can be used as the driving unit of minimally invasive surgical instruments. However, at present, the response time is too long. It is necessary to improve the response speed by optimizing the crosslinking density.

3.3 Smart Composites

Intelligent composite materials, through the collaborative design of "flexible matrix+functional filler", integrate multiple functions such as driving and perception, break through the limitations of single material performance, and are the core carrier of "structure function integration" of soft robot. It is based on silicone rubber, PDMS, TPU and other fillers, such as composite magnetic particles, graphene, gold nanorods, to achieve precise sensing, remote driving and other functions.

The team of Harbin Institute of technology has prepared the $\text{Fe}_3\text{O}_4/\text{PDMS}$ composite thin-walled soft robot through the light curing 3D printing technology. The minimum wall thickness is only 200 μm , and it can bend 360 ° under 0.5 T magnetic field, successfully completing the capture of simulated vascular foreign bodies [16]. However, such materials generally face the problems of filler agglomeration and weak interface bonding, which need to be optimized by surface modification and other technologies to improve the performance stability.

The Figure 3 summarizes the above information and clearly presents the material system level.

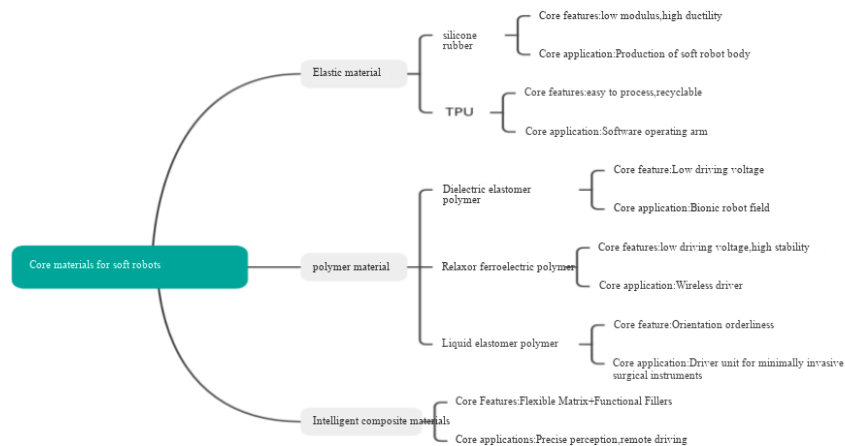


Fig. 3. Core material tree view (Picture credit: Original)

4 Material Adaptability in Different Scenarios

The core of software robot scene application is the accurate matching of material performance and environmental constraints: underwater needs to withstand high pressure, low temperature and corrosion, medical scenes need biocompatibility and precise drive, and industrial environment focuses on temperature resistance, wear resistance and chemical stability. At present, elastomers, polymers and smart composites have achieved multi scene preliminary adaptation through functional modification, but it is still necessary to coordinate the balance between function and preparation.

4.1 Underwater Environment

The core requirements for materials in underwater scenes are pressure resistance and corrosion resistance, while maintaining the stability of driving response. The team of Harbin Engineering University designed the "polyethylene shell+poly α - olefin dielectric fluid" to keep the driver at a bending angle of 48.8° at 110 MPa and 2°C . The deep-sea speed of the soft robot based on this material is 7.2 cm/s, and no additional pressure resistant shell is required [17]. The Peking University team prepared the "10GPa carbon fiber reinforced epoxy resin+1mpa dielectric elastomer" composite layer by vacuum hot pressing at 80°C and 2 MPa, which can withstand 2 MPa water pressure and achieve 10% strain, and is suitable for shallow water detection and sample collection [6]. At present, the main challenge is that low temperature will shorten the endurance of material driven energy system and accelerate the aging rate of materials under deep-sea water pressure. It is necessary to further optimize the interface bonding and anti-aging coating technology.

4.2 Medical Scenarios

In the medical scene, biocompatibility is the primary premise of materials, which need low modulus, degradable or precise driving. Zhejiang University prepared starch hydrogel through solvent control, with modulus of 36.0 – 205.8 kPa, tensile strain of 361.4%, and complete degradation in 24 days. The pneumatic soft gripper based on this material has been successfully applied to food grade medical operations [18]. The current problem is that the mechanical strength of biodegradable materials is generally insufficient, and the biological safety of long-term implanted materials still needs to be based on a large number of animal experiments.

4.3 Extreme/Industrial Environments

Extreme/industrial environments have strict requirements on the temperature resistance, wear resistance and structural stability of materials, and some scenes also need to meet the cleanliness standard. The thermal decomposition temperature of carbon nanotube reinforced composites exceeds 500°C , and the retention rate of mechanical properties at 150°C is 85%. At present, carbon nanotube reinforced composites have been used to manufacture the core driving parts of engine compartment inspection robot, which can withstand continuous high temperature and mechanical vibration [19]. High temperature materials need to consider both high temperature resistance and creep resistance, and corrosion-resistant materials need to balance corrosion resistance and mechanical strength. At present, it is necessary to continuously strengthen and improve the performance of the structure to improve the utilization rate of materials.

5 Integration Trend of Emerging Materials and Machinery

At present, the core contradiction faced by soft robots is that there is a natural imbalance between the flexible advantages of soft materials and the demand for mechanical functions. Although traditional elastomers can adapt to complex environments, they lack key performance such as torque transmission and extreme environmental tolerance; Although the rigid structure can guarantee the function, it sacrifices the safety and adaptability. Therefore, the research and development of emerging materials should be guided by the "actual needs of mechanical systems"; At the same time, mechanical design needs to actively adapt to the characteristics of new materials and build a new system of flexibility and functionality.

At Present, the integration of materials and machinery is jumping out of the traditional mode of "passive adaptation of materials to mechanical structures" and moving towards a new stage of deep collaboration of the whole chain. In the process of manufacturing and maintenance, the limitations of "assembly" integration of heterogeneous materials are broken, and the seamless connection of sensors, actuators and soft substrates is realized, which not only avoids the problems of easy wear and failure of traditional interfaces, but also enables the mechanical structure to dynamically adjust its shape with the characteristics of materials; At the same time, this fusion compresses the response delay to millisecond level through the Trinity cooperation of sensing, decision-making, execution, and significantly improves the grasping accuracy and environmental adaptability.

6 Conclusion

In this paper, the research status of soft robot materials is systematically reviewed. The results show that the preparation technology has formed a multi-element system dominated by 3D printing, supplemented by composite lamination and textile weaving, which can realize the integrated molding of complex structure and multi materials; The core materials cover elastomer, polymer and intelligent composite materials, which play a key role in structural support, driving response and multi-functional integration respectively. They have achieved preliminary adaptation in underwater pressure resistance, medical biocompatibility, industrial temperature resistance and other scenarios, but they still face problems such as insufficient mechanical properties and short endurance in extreme environments. To sum up, the material performance is the core to determine the function and scene adaptability of soft robot. Although the current research has constructed a multi-dimensional development pattern, it is necessary to further balance the material function, preparation cost and environmental adaptability. This research provides a systematic reference for material selection and technology optimization of soft robot, promotes the cross integration of material science and mechanical engineering, and helps the technology implementation of key application scenarios. It is hoped that future researchers will continue to improve the integration of machinery and materials and promote the application of soft robots.

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