Multi-material 3D-Printing Soft Robot Functional Component

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Abstract—3D printing has a wide range of applications and addresses many challenges inherited from conventional manufacturing techniques. This paper presents a dual-extrusion 3D printing platform capable of printing soft materials for soft robot functional components. Dow Corning-737 and Dragon Skin-0030 materials are used. Single-line experiment is used to determine the optimization parameters of extrusion pressure, printing speed, and layer thickness of the developed multi-material 3D printing platform. A soft valve consisting of two soft materials has been fabricated, and the printed soft valve is verified by a performance experiment. The results indicate that the developed 3D printing platform can fabricate soft robot functional components at high speed with high accuracy.

1. Introduction

Soft robots are now a hot spot and development frontier of robotics [1]. Compared with traditional rigid robots, soft robots show good environmental adaptability and human-machine interactivity. Soft robots are mainly controlled and driven by traditional valves, pumps and electronic components with rigid materials, which are bulky and heavy [2], greatly limiting the portability and functionality of soft robots. Recently, many soft robot functional components [3-4] have been developed instead of rigid valves, pumps and electronic components to improve the performance of soft robots. 3D printing is an additive manufacturing process that adds materials layer-by-layer to build complex models digitally represented in computer-aided design (CAD) systems. The distinguished advantage of 3D printing is that it is a mold-less process, suitable for freeform and complex geometrical model realization, which is the most suitable method for manufacturing soft robot functional components [5].

At present, some researchers have developed methods to print multi-material soft robots. Whitesides et al. [6] developed a combustion-powered soft robot whose body transitions from a rigid core to a soft exterior with 3D printing. Wood et al. [7] used 3D printing technologies to fabricate the world's first entirely soft robot named Octobot. He et al. [8-9] manufactured a soft sensor composed of liquid metal and silica gel by multi-materials 3D printing. Yu and Wang [10] manufactured a gradient magnetic soft actuator by 3D printing, which can be deformed with the change in the magnetic field.

The above studies are focused on the application of 3D printing technology for soft robot functional components. There are only a few studies on the optimization of printing parameters in the 3D-printing process. In this paper, based on the developed multi-material 3D printing platform, two soft materials, Dow Corning-737 and Dragon Skin-0030, are used to fabricate the designed soft robot functional component. Single-line and single-line wall printing experiments are used to determine the optimization parameters of extrusion pressure, printing speed, and layer thickness of the 3D printing platform. A soft valve consisting of two soft materials was fabricated. The results indicate that the developed 3D printing platform can fabricate soft robot functional components accurately.
2. The 3D printing platform and materials

2.1. The 3D printing platform

Based on the traditional fused deposition modeling (FDM) 3D printing platform, two FDM nozzles are replaced with pneumatic extrusion nozzles. In addition, the air pump is integrated with the 3D printing platform, and the system can automatically control the pneumatic extrusion nozzles to print complex soft objects such as soft sensors and soft robots (shown in Fig. 1).

Fig. 1 The 3D developed printing platform. (a) Nozzle module, (b) 3D printing platform, (c) The control module

2.2. The materials

In this paper, Dow Corning 737 silicone gel and Dragon Skin-0030 two-component silicone gel are selected for printing. These two materials have different elasticities and can be used as materials for soft robot functional components.

Dow Corning 737, a silicone elastomer (also known as moisture-curing silicone), has the advantages of high fracture elongation, tensile strength, and fatigue life. Dragon Skin 0030 is used as the main material for PDMS, and platinum-cured silica gel is divided into two parts (base material and cross-linking agent), which are cured into solid rubber after mixing. To improve the printing quality, a 1% thickener agent was added to increase the viscosity of the silica gel material.

If the viscosity of the printing material is too high, the material cannot be extruded, while if the viscosity is too low, the extruded soft material cannot be stacked and molded. Kinexus pro+(shown in Fig 2) from the Malvern Instruments was used to test the rheological performance of Dragon Skin-0030, Dragon Skin-0030 with a 1% thickener and Dow Corning 737(shown in Fig 3).
Fig. 2 Kinexus pro+ (Malvern Instruments)

Fig. 3 Test results of rheological properties: (a) Dragon Skin-0030, (b) Dragon Skin-0030 with 1% thickener, (c) Dow Corning 737

The storage modulus reflects the elastic size of the material, and the loss modulus reveals the viscosity. When the material is in a solid-state, the storage modulus is much greater than the loss modulus; when the material is in a liquid-state, the loss modulus is much larger than the storage modulus; and when the storage modulus is approximately equal to the loss modulus, the material is in a gelatinous-state. It can be extruded smoothly, and the material can be used as printing material in the developed platform.

3. Experiments

3.1. Printing process parameter optimization

A single-line printing experiment was used to determine the appropriate print parameters, such as the viscosity extruded pressure (P), and nozzle moving speed (V). This experiment adopts a soft 3D printing platform with an extruding nozzle whose diameter is 0.41 mm, and the printing material is
Dragon Skin-0030 with 1% thickener. This experiment shows that the extrusion pressure and nozzle moving speed affect the extrusion line width. The two ends of the single-line printing structure are unstable. A microscope can be used to measure the width of the middle section of the print line. We measured five times and selected the average numerical value (shown in Fig 4(a)).

When the nozzle moving speed is under the situation of V=5 mm/s, V=10 mm/s, V=15 mm/s. We studied the effects of different air pressure sizes on the extrusion line diameter. The Single-line formation quality is shown in Fig.4(b), yellow indicates that it cannot be printed under this condition. Green represents that the single line can be printed well; red represents that the diameter of the line is much broader than the extrusion needle diameter, which means that the parameters above are not suitable for printing. Therefore, we focus on how the extrusion pressure affect the line diameter when V= 10 mm/s.

In the case of nozzle moving speed V=10 mm/s, P<26 psi, the deposited silicone gel is discontinuous due to the extrusion rate being too low, and the extruded line diameter is far less than the diameter of the nozzle; when the nozzle moving speed V=10 mm/s, P>36psi, the filament width is approximately 0.51 mm, which is larger than the nozzle diameter, these two situations are not suitable for high-precision 3D printing.

When the extrusion pressure is between 26-36 psi, the extruded line is uniformly stable and suitable for high-precision 3D printing. Here, we select 32 psi as the extrusion air pressure and the line diameter is approximately 427 µm. The relationship between the line diameter and the air pressure is shown in Fig 4(c).

3.2. Printing of soft valve

Drawing lessons from the on-off principle of rigid valve[11], an elastic membrane is designed inside the soft valve structure. The thickness of the elastic film is small, which is similar to a thin plate structure and can be significantly deformed under lower pressure. Under normal working conditions, the airflow normally flows from the inlet to the outlet. When pressure is applied to the control chamber, the membrane is forced upwards against the entrance, blocking the gas. The specific structure is shown in Fig 5a. To reduce the upwards protrusion distance of the film and reduce the pressure required to close the valve in the control cavity, a hollow boss structure is set at the entrance. This structure can reduce the convex distance of the film, increase the durability of the film, and limit the axial displacement of
the film so that the valve can be closed more thoroughly.

The material of the soft valve is composed of Dow Corning 737 and Dragon Skin-0030+1% thickener samples. Dow Corning 737 has better elasticity than Dragon Skin-0030. Therefore, Dow Corning 737 silicone is used to print the elastic film part of the flexible valve, and the rest of the main body is made of Dragon Skin 0030 silicone.

White pigment was added to Dow Corning 737 silica gel to make it easy to distinguish. Black pigment was added to Dragon Skin-0030 silica gel. The soft valve is printed by the multi-material 3D printing platform mentioned in section 2. The printed process diagram is shown in Fig 5b.

3.3. Experiment on soft valve

The width of membrane of the soft valve is 0.9 mm. When the membrane of the membrane is too enormous, the pressure required for membrane deformation is also large, and the closing pressure of the valve is also large. The inlet of the valve takes a constant pressure source of 10 kPa. As shown in the Fig 6b, the valve closing pressure of the 0.9 mm thick film is 80 kPa, and when the membrane first deforms, due to the small deformation of the membrane, the valve closing range is small, and the slight closing of the film has no effect on the flow rate. As the deformation of the membrane increases at 20 Kpa from 0 to 80 Kpa, the degree of the valve closure increases as the pressure changes, and the degree of membrane closure has an increasing influence on the flow rate. As the degree of deformation of the film increases, the pressure required for the deformation of the film increases. (shown in Fig 6b).

4. Conclusion

In this paper, a 3D printing platform with dual-extrusions has been built. A 3D printing solution for the
two-component Dragon Skin-0030 silicone gel is designed and performed. To improve the printability of two-component silicone gel, silicone thickener should be added through theoretical analysis and experiments. Through single-line printing experiments, the most suitable 3D printing parameters for Dragon Skin-0030 silicone are obtained.: extrusion pressure= 32psi, the needle moving speed = 10mm/s, and the layer height = 0.30mm. A new soft valve composed of two materials was printed based on the optimal printing parameters though single-line experiments. The soft valve is a normally open valve, which is closed under the action of air pressure. Experiments have been carried out to determine the closing pressure of the soft valve.

On the other hand, the printing strategies for the generality of silicone soft materials need to be further studied. More tests on the soft valve are required to verify the functionality and detailed performance parameters of the soft valve.

Acknowledgments
This work was supported by National Natural Science Foundation of China (Grant No. 61773274).

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