博　士　論　文　の　内　容　の　要　旨

氏名	LI CHONGCHAO
学位名	博士（工学）
学位授与年月日	2021 年 3 月 20 日
論文題目	Development of soft actuators based on plasticized thermoplastic polyurethane and their applications （ポリウレタンの可塑化によるソフトアクチュエータの開発と応用に関する研究）

（博士論文の内容の要旨）

As interesting alternatives to conventional soft actuators, electroactive actuators based on plasticized thermoplastic polyurethane (TPU) have shown their potential in developing soft robotics due to the large bending deformation, fast response, and good durability, especially their designable properties. In this dissertation, gels and actuators were fabricated using TPU and their various properties were investigated.

Many soft gel samples based on four types of TPU and different contents of plasticizer (dibutyl adipate (DBA)) were successfully prepared, and the dielectric and mechanical properties of these samples were firstly tested. The dielectric constant of these samples decreases with increasing frequency and tends to become constant at high frequencies. It was also found that the plasticizer has a major influence on both the dielectric constant and the elastic modulus of plasticized ET (one type of TPU) gels. The dielectric constant increased with increasing DBA content up to 85.7 wt% and then decreased. However, the Young's modulus of these samples decreased continuously with increasing addition of DBA, and the elongation at breakage was more than 900% for all the samples. The results for the mechanical properties indicated that the samples became softer with increasing addition of the plasticizer. According to these results, the plasticized ET gels were considered to have the most suitable dielectric and mechanical properties for optimizing the performance of soft actuators. Therefore, ET-DBA gels were selected from all four TPU types used in this study and used for further experiments.

Next, ET based soft actuators with different plasticizer content were prepared and the actuation performances were investigated. At an electric field of 2.86 V μm-1, the bending displacement of ET-DBA actuators increased with the DBA content until 85.7 wt% and then decreased with more DBA addition, resulting in the largest bending displacement of 12.11 mm among all samples. And an increase in voltage also caused an increase in the bending displacement of ET-DBA actuators. Besides, a wide response ability in the frequency region from 0.5 Hz to 10 Hz was confirmed, and the largest amplitude over 22 mm of the actuator was observed at 5 Hz. Furthermore, a new method was proposed to estimate the tiny force generated by the actuator (0.7 – 1.4 mN). The small variation (less than 3%) of the measured results indicated that the proposed method is reliable even at a small bending angle. It is believed that the rapid bending capability and large deformation of the developed actuators at low intensity of electric field will make their considerable contributions to the field of soft robotics or biomaterials.

Apart from the actuation performance, understanding the mechanism is also essential for controlling soft actuators as well as developing novel ones. Therefore, the actuation mechanism of plasticized thermoplastic polyurethane under the effect of an electric field was also studied in this thesis. The behaviors of the plasticizer and TPU membranes in electric fields were investigated and observed in-situ by a microscope, showing that the plasticizer molecules migrated towards the anode of the actuator. It is proved that there was a very thin plasticizer-rich layer formed in the material because of the accumulation of plasticizer molecules carrying negative charges, basing on the results of electrochemical impedance measurement and space charge measurement. This further led to a lower Young's modulus but an internal electric field with higher density in this layer, resulting in the deformation of the actuator. Based on the actuation mechanism, some actuation characteristics of the developed soft actuators were clarified. The maximum bending displacement of these actuators increased with the number of cycle tests because of the activation of the plasticizer; and in each cycle test, the bending displacement quickly reached the maximum value and then gradually decreased. It is considered that these characteristics are strongly related to the behaviors of plasticizer molecules, which were investigated later. It is believed that the understanding of the actuation mechanism and characteristics will be very helpful for controlling flexible actuators as well as designing novel artificial muscles and soft robotics. As an example, cylindrical TPU actuators were developed according to the mechanism and the actuation performances were studied in the following experiments.

The TPU gels and actuators that were developed in this work provide a novel route for improvements in artificial muscles and soft robotic systems. The superior dielectric and mechanical properties and outstanding actuation behaviors of plasticized TPU suggest that it is not only a potential material for use in actuators and sensors but also that it can be applied in fields including piezoelectricity, energy harvesting, electronic engineering, and aerospace engineering.