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Novel high-Cycle-Life Soft Actuator using silicon elastomer matrix and ethanol

Hojat Zamyad[1] Amirhossein Ebrahimi[2]
Samaneh Sahebian[3] Jvad Safaie[4*]

1- Introduction

Movement mechanisms in biological systems have always inspired engineers to design and develop multi-purpose robotic systems. The innovations and creative results of this have led to a new field in robotics, called "soft robots", with special features compared to conventional ones. The structure of ordinary robots is composed of high-strength durable materials e.g., steel, stainless steel, aluminum, titanium, etc., while the soft robots are made of very high tensile materials such as polymers and rubbers.

In the present study, an independent integrated soft operator was developed to produce a mechanical force by the liquid-to-vapor phase changing of a secondary component in the polymer structure. It responds to electrical stimulation, and introduces a new generation of soft and powerful actuators without any external independency. Composite characterization and evaluating of its chemical-structural relationship are indispensable for engineers who work in this domain. Therefore, an elastomeric composite was made with the optimal ethanol volume and the motor behavior of this artificial muscle was assessed in different working cycles during several days. Moreover, the core/surface temperature of soft actuator was evaluated as a key factor along with its motor behavior.

2- Materials & Methods

2-1 Material. For a polymer matrix selection and the related phase-changing fluid, several aspects were considered, e.g. polymer mechanical properties, boiling point of the secondary phase and matrix-fluid chemical compatibility. Finally, two-component silicon elastomer (silicon and hardener) and ethanol (with a purity more than 99.5% and a boiling point of 78.32°C, "Sigma Chemistry", Iran) were used as a composite matrix and a phase-changing fluid, respectively. Also, to generate joule heat, a spring-shaped nickel-Chrome (Ni-Cr) wire resistance (0.25mm) was embedded inside the actuator for electrical stimulation.

2-2 Composite fabrication. Based on previously reported research in Columbia University, a silicon-ethanol composite was prepared by mechanical mixing with an optimal amount of ethanol, which has been 30% volume. After 5min mixing, the hardener was added with a ratio of 1/50 related to the silicon weight and mixing was continued for 2min. Then it was cast in a polymethyl methacrylate mold with 90×15×15mm dimension. A 75cm spring-shaped Ni-Cr wire was embedded in the center of the mold and then cured 4 hours at room temperature.

2-3 Data recording hardware. To investigate the surface morphology and size of cavities inside silicon-ethanol composite, Field Emission Scanning Electron Microscope (FESEM) was used under 10KV accelerating voltage. The sample was refrigerated and the fracture surface was coated with gold spray before scanning, in order to prevent electric charge accumulation over the surface and create a high-resolution image. The R&S NGPV power supply was used for electrical stimulation. 12 watts electrical power (20V/0.6A) was applied in each cycle. To measure core/surface temperature of actuator during each cycle, Pt1000/LM35 sensors were applied, respectively. A digital camera was also used to record the soft robot's movement. In order to simplify and ameliorate the accuracy of monitoring, the camera was placed perpendicular to the sample and record muscle deformation during the experiment.

3- Results

3-1 Motor behavior investigation and temperature response of the soft actuator on the first working day.
Figure 1 and Figure 2 show the temperature and movement response of the composite actuator in 15 successive working cycles on the first working day. The temperature changes regularly; however, its displacement varies in different working cycle. According to Figure 1, due to electrical stimulation and joule heat, the actuator core/surface temperature change in the range of 55-80°C/40-47°C respectively. The larger core temperature range (25°C) compared to surface (7°C) could be related to the intense heat exchange of the actuator surface with the surrounding environment.

With 78°C core temperature, the expansion rate of material increases due to the boiling point of ethanol. It seems that after some working cycle, different parts of the sample are heated enough and a higher amount of ethanol reaches the phase transfer temperature inside the composite, therefore, the actuator displacement

[1] Ph.D. Student Department of Electrical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
[2] M.Sc. Student Department of Materials Science and Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
[3] Assistant Professor, Department of Materials Science and Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
[4] *Corresponding Author: Assistant Professor, Department of Electrical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran. Email: safaie@um.ac.ir

increases. At the end of the fifteenth working cycle, the amount of longitudinal displacement reaches to 11mm.

3-2 The aging effect on motor behavior and temperature response of soft operator. The silicon structure is not closed; so, ethanol gradually passes through the polymer chains under internal pressure and leaves the composite structure. Therefore, the movement ability becomes limited, since the ethanol phase changing is the reason of actuator expansion. On the other hand, ethanol is a powerful energy absorber; Therefore, its removal from the composite structure will lead to a temperature increase in the actuator .Table 1 shows the related aging effect. Based on the recorded data, the ethanol removal from material structure during different working days was led to limited actuator movement and increased temperature (except for the second day). It should be noted that the increased operating temperature causes structural damage in the composite gradually.

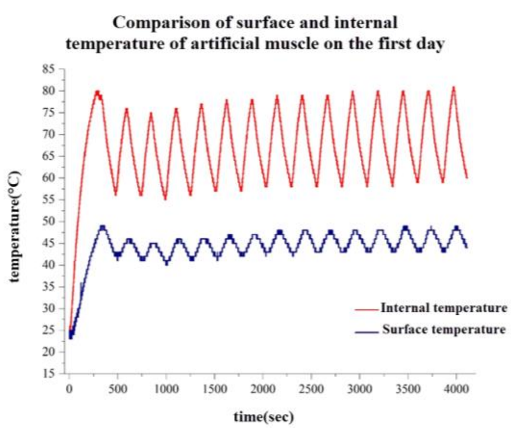

Fig. 1: Temperature response of soft robot to the successive cycles on the first working day

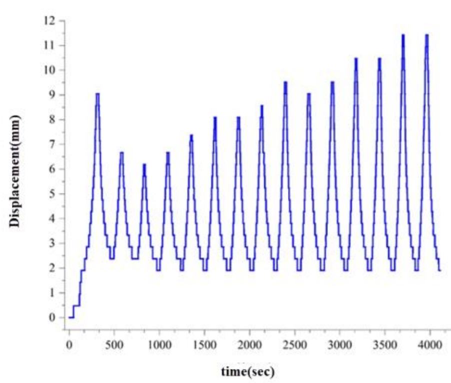

Fig. 2: Dynamic operation (Longitudinal displacement) of soft robot in successive cycles on the first working day

Table I: actuator mass change (due to ethanol release) and comparison of motor and temperature response on different working days

Working days	First	Second	Fourth	Seventh
Sample mass at the end of 15 working cycles (%)	95.16	91.82	90.15	89.02
Average of maximum displacement (mm)	8.55	6.2	3.61	2.85
Average of maximum core temperature (°C)	78.9	73.1	81	81

3-3 Microscopic structure of the composite. to evaluate the microscopic structure of the soft robot, the composite was refrigerated and broken after 15 excitation cycles on the seventh day, and the fracture surface was observed using FESEM. As shown in Figure 3, ethanol is homogeneously distributed inside micron-sized capsules with smooth surfaces (Figure 3-a) and larger air bubbles (Figure 3-b).

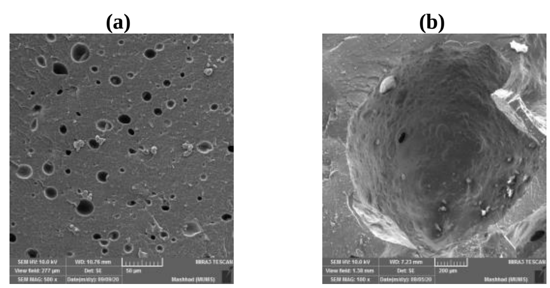

Fig. 3: Microscopic structure of silicon/ethanol composite on day 7 after 15 working cycles
a: Smooth microcapsules with micron dimensions
b: Air bubbles with millimeter dimensions

4- Conclusion

In this study, a composite artificial muscle was made of silicon elastomer as the base matrix and ethanol as the phase-changing fluid. The results of study showed that by electrical stimulation of the composite on different working days, ethanol is gradually removed from the structure of the actuator and as a result, the temperature of the material increases and the ability of dimension changing decreases. Despite the relative increase in temperature of the composite core, the material showed good thermal stability. Also, based on the observations made on the microscopic structure of artificial muscle using FESEM, it was found that ethanol was homogeneously distributed throughout the silicon matrix.