Liquid Crystalline Elastomers for Microengineering

Actuator Materials. Liquid crystalline polymers are not just high-performance materials for applications requiring resistance to particular stresses. Special functional liquid crystalline elastomers (FULCE) produce movements that make it possible to develop new technical actuators based on the principle of the human muscle. The technology, mode of operation and use of these effectors are described using the example of a hybrid microgripper.

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Seven European research groups in the “FULCE” Research Training Network funded by the European Union have been working on functional liquid crystalline elastomers (FULCE) since 2003. The aim of the Ilmenau research group is to integrate these novel elastomers with actuator properties effectively into micromechanical systems.

Creating Actuator Properties

The characteristic feature of polymers is their long-molecular-chain structure. Liquid crystalline polymers (LCP) combine these polymer properties with the anisotropy of liquid crystals. Special crystalline molecular units (mesogens) are responsible for the crystalline behaviour. There are basically two ways in which these mesogens can be combined with polymer chains [1]: in the case of main polymer chains, the mesogens can be inserted directly into the polymer chain to produce liquid crystalline main-chain polymers. With side-chain polymers, on the other hand, the mesogen are joined to the polymer backbone using a spacer. In this case, polymerisation of the backbone can take place before or after attaching the mesogens. Since the backbone and mesogens can be created independently of each other, production of side-chain LCP is easier to control than production of main-chain LCP [2].

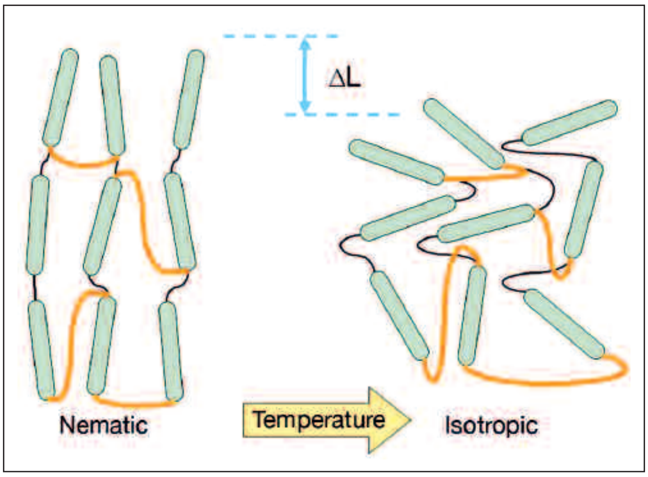

Fig. 1. Schematic diagram of the nematic-isotropic transition of special crystalline molecular units (mesogens)

Liquid crystalline elastomers (LCE) are produced by weak crosslinking of LCP. Owing to the low density of the polymer chains, the resulting material has rubber-elastic properties (Table 1). Siloxanes are a particularly interesting backbone, to which the mesogen can be attached by platinum catalysis.

Properties		Values
Hardness	Shore A	10–80
Tensile strength	MPa	0.2–0.6
Actuator stress	kPa	21–60
Uniaxial deformation $(L_0/L)*100$	%	140–160
T_{NI}	°C	30–120
T_G	°C	-10–24

Table 1. Some typical properties of liquid crystalline elastomers

To obtain actuator properties, it is vital for the mesogens to be oriented as uniformly as possible within the network, i. e. the material must be highly anisotropic. The elastomers with mesogens in the side chains (side-chain LCEs) used by the Ilmenau group were produced by the University of Freiburg/Germany [3]. Mesogen orientation in these side-chain LCEs was achieved by uniaxial mechanical stretching of the material. The material crosslinking necessary to obtain elastomeric properties starts immediatley before mechanical stretching and so “freezes” the ordered molecular arrangement achieved by stretching.

When the temperature is increased in the immediate environment of actuator material produced by this method, the ordering of the mesogens is lost [4]. The reason for this change of shape is the transition of the material from the liquid crystalline to the isotropic phase by thermal fluctuation (nematic-isotropic transition; Fig. 1). The reversibility of this change depends on the elasticity of the

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Transition process

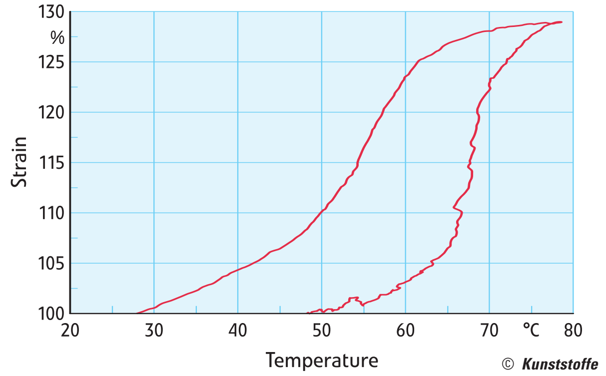

Fig. 2. Strain-temperature diagram of thermoactive FULCE (Functional Liquid Crystalline Elastomers)

network, which restores the original state of orientation during the back transformation. This causes macroscopic contraction of the actuator film. Fig. 2 shows this thermomechanical transition process in a temperature-strain diagram.

FULCE actuators are capable of performing different mechatronic functions under low mechanical stress and high strain. FULCE are often described as "artificial muscles", which indicates the physical properties and application potential of the material. A strain of up to 400 % and mechanical stress of up to 100 kPa are theoretically predicted. A strain of up to 140 % and maximum mechanical actuator stress of 41 kPa have already been demonstrated experimentally.

Production of Microgrippers

On the basis of the knowledge gained from the characteristic curves in Fig. 2, the gripper/manipulator in Fig. 3 was designed at Ilmenau. The aim was to show that it is possible with minimal loss to position a load with the aid of FULCE actuators and hold the load in this position for a sustained period of time without any problem. The arm structure shown in Fig. 3 is the first microtechnological application of FULCE actuators achieved through microintegration. To minimise the motion loss of the system, elastic silicone joints were used in this prototype.

To produce electric terminals, the silicon wafer is first masked and metallised with copper (lift-off process). Then both sides undergo dry chemical etching processes (RIE → oxide etching, ICP → Si etching) to create the arm structures and areas for the joints and actuator film. Following this, the actuator film is applied (hybrid) onto the prepared anchoring point. Placement of the film can be carried out in two ways: the silicon surface and actuator film can be activated with oxygen plasma, which gives better adhesion between the two surfaces [5]; or the actuator film can be directly embedded in the silicon. Previous experiments have demonstrated that for electrothermal excitement of the actuator, a FULCE prepolymer solution made electrically conductive with carbon black can be applied onto the surface (50 to 80 µm thick). The microgripper in Fig. 3 uses another method to heat the environment of the film. 8 to 10 windings of gold wire (25 µm thick) are wound around the film. The disadvantage of the conductive polymer layer as compared with the wound gold wire is that because of its direct contact with a passive layer on the surface, an 8 to 10 % motion loss is caused. It is expensive and enables geometric lengths of up to about 10 mm to be obtained.

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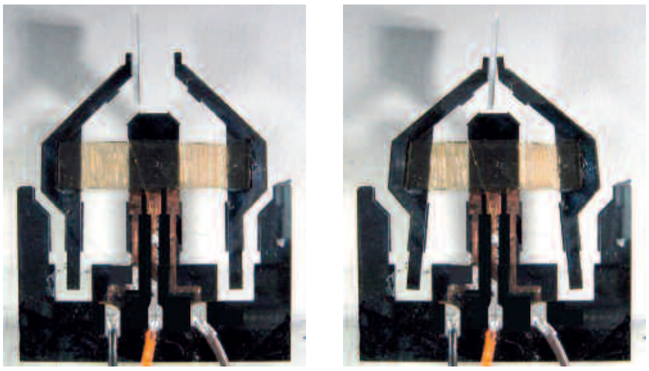

Fig. 3. Open (left) and closed (right) microgripper: FULCE microgripper with elastic joints, arm length 20 mm, frame dimensions: 22 × 25 mm^2

To produce the joint arms, the joints are filled with silicone. Then a laser cuts the arm structures free, which also removes the thin supporting structures deliberately produced during the dry chemical etching process. When the arms have been cut out, they are only connected to the silicon base structure by elastic elements. Laser cutting offers the advantage that the elastic structures are not subjected to any mechanical stress while the arms are being cut free. The effect of heat during the cutting process is minimised by the good thermal conductivity of silicon so that the actuator film is not damaged by heat.

Successful Experiment

The experiments show a linear curve for the joint characteristics. Actuator stress reaches a maximum value of 41 kPa at 80 °C with a cross section of 1.1 mm^2. For the geometry in question, this means that at the maximum actuator stress the actuator loss caused by the restoring force is about 52 % of actuator performance.

When the control voltage is altered, the temperature around the actuator also changes. This induces a mechanical stress and so ultimately causes a movement of the arms. Fig. 4 shows strain as a function of applied control voltage for the "excite, hold, relax" cycle at different voltage increase rates. Fig. 3 shows the open and closed gripper.

Switching frequencies of up to 0.15 Hz can be achieved. The response time to within ±5 % of the final position is about 50 s. Such actuators are suitable for slow, sensitive positioning and gripping movements.

With the prototype of a gripper/manipulator, the aim was to show that by using elastic passive elements it is pos-

Gripper curves

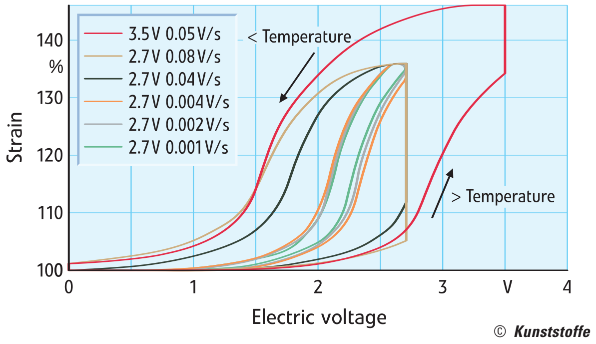

Fig. 4. Linear excitement curves for the gripper at different excitement rates

sible to employ liquid crystalline elastomers in microengineering components to place loads in defined positions and hold them in these positions for a certain time.

Potential Applications

The above-mentioned application or principle can be used for micromounting optical components and SMDs or adjusting such elements to any required position by switching or moving optical fibres. The extreme deformability of FULCE materials in comparison with piezoelectric materials permits verylarge movements. The similar molecular structure of FULCE materials to PDMS [poly(dimethyl siloxane)] allows them to be combined with PDMS materials. Like PDMS, FULCE materials withstand heat and are resistant to most acids and bases, so that they can be used in aggressive environmental conditions.

So far only themomechanical actuators have been considered. In future, with only a small change to the microtechnology, it will be possible to adapt existing optomechanical FULCE materials for actuators that can be used in different applications such as pumps, valves and switches. At Ilmenau, we are working on the first demonstrations of micromechanical systems with controllable membranes. The aim here is to combine folded structures of PDMS with FULCE actuators to obtain hybrid integrated controllable membranes. ■

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