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Muscle-like high-stress dielectric elastomer actuators with oil capsules

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Abstract. Despite being capable of generating a large strain, dielectric elastomer actuators (DEAs) are short of strength. Often, they cannot produce enough stress and as much work as those achievable by human elbow muscles. Their maximum actuation capacity is limited by electrical breakdown of dielectric elastomers. Often, failures of these soft actuators are pre-mature and localized at the weakest spot under high field and high stress. Localized breakdowns, such as electrical arcing, thermal runaway, and puncture, could spread to cause ultimate rupture if they were not stopped. This work showed that dielectric oil immersion and self clearable electrodes nibbed the buds of localized breakdowns from DEA. Dielectric oil encapsulation in soft membrane capsules was found to help the DEA sustain an ultra-high electrical breakdown field of 835MV/m, which is 46% higher than 570MV/m, the electrical breakdown field in air. As a result of the increased apparent dielectric strength, this oil-capsule DEA realizes a higher maximum isotonic work density up to 31.51J/kg, which is 43.8% higher than that realized by the DEA in air. Meanwhile, it produces higher isometric stress up to 1.05MPa, which is 75% higher than that produced by the DEA in air. Such improved actuator performances are comparable to those achieved by ‘human flexor muscles’, which can exert up to 1.2MPa during elbow flexion. This muscles-like high stress dielectric elastomeric actuation is very promising to drive future human-like robots.

1. Introduction

Dielectric elastomer actuators (DEAs) have been reported with great actuation potential. For example, a flat pre-strained DEA has demonstrated a large areal actuation strain of 158% under high Maxwell stress (7.2MPa at a high electrical breakdown strength of 412MV/m) [1]. With such great actuation potential, DEAs are promising to act as artificial muscles. They have been applied to drive human-like robots[2, 3]. However, they are not as strong as human flexor muscles to produce high enough stress change. Typically, human flexor muscles can achieve a higher stress change up to 0.8-1.2MPa during elbow flexion[4]. DEAs in the roll form were used to drive an arm-wrestling robot, but they realized only a moderate stress change up to 0.23MPa at 74.1MV/m[2]. The realized stress change is a lot smaller than the best reported potential [5], due to reduced electrical breakdown strength under the operating condition. Not to surprise, the DEA-powered arm-wrestling robot lost in a match with a young human opponent[6].

To act as strong artificial muscles, DEAs need to generate a higher Maxwell stress. However, their maximum capacity to generate stress change and work is often limited by electrical breakdown of dielectric elastomers. Being a soft capacitor, DEAs may break down like any metalized plastic capacitors[7, 8, 9, 10]. They are subjected to various failure modes as shown in Fig. 1(a), for examples: partial discharge[11], electromechanical instability[12, 13, 14], electronic avalanche[15, 16], and electrothermal breakdown[17]. Often, their failure is pre-mature and localized at the weakest spot. As a result, their operating electric field could be lower than the best reported electrical breakdown strengths of the same dielectric material.

The past research has greatly enhanced the electrical breakdown strength of dielectric elastomer by means of pre-stretching [1, 18] and using self-clearable electrodes[19]. For example, electrical breakdown strength of acrylic elastomer has increased from 34MV/m at zero pre-stretch to 200-400MV/m at high pre-stretch [1, 12]. Pre-stretch helps stiffen[14] the dielectric elastomer and suppress air voids[11] in it. On the other hand, use of self-clearable electrode material can stop localized breakdown from prematurely failing a DEA. Self clearing of DEA happens when the electrode materials at the breakdown spot are burnt off (i.e. oxidized or vaporized) and thus the defective spot is electrically isolated from the rest of the conductive electrode [19, 9, 20].

To produce axial actuation like muscles, DEAs are often configured in the pure shear boundary condition, where their highly pre-stretched film is laterally clamped and kept a constant while it elongates under electrical activation. They are suitable for producing axial force to do work, such as lowering a deadweight. In theory, with the help of lateral clamping, these pure-shear DEAs can sustain an even higher electrical breakdown strength by avoiding the electromechanical instability [21, 22, 16, 23]. However, in practice, they still succumbed to failure by electronic avalanche at an electric field, well below the anticipated high electric field[16, 23]. We believe that oil immersion can help these pure-shear DEAs avoid electronic avalanche, just like it did previously

to a flat membrane DEA, which was equi-bi-axially pre-stretched and fixed onto a rigid frame [19, 24].

Previously, a bath of dielectric oil was used to immerse flat membrane DEAs[19, 24]. The oil bath keeps air away from the DEAs and it helps extinguish electric arcing[19, 24] and thermal runaway that may have pre-maturely damaged the DEAs[17], as shown in Fig. 1(b)-(c). Oil immersed flat DEAs were reported to a very high breakdown electric field up to 800MV/m[17]. However, the oil bath used is not portable and it is too greasy to be interface with the external load. In this paper, we propose using soft membrane capsules to encapsulate oil over a pure-shear DEA. These oil capsules can conform to axial deformation of the DEA. Under oil immersion is the self-clearable graphite-powder compliant electrodes. This combination will be subsequently shown to help the pure-shear DEA sustain an ultra-high electric field up to 835 MV/m and realize a high maximum work density of 31.51J/kg.

Figure 1. (a) Failure modes of DEA at a range of electric fields, (b) electrical arcing and thermal runaway causing terminal breakdown of DEA in air, and (c) oil immersion damping out electric arcing and thermal runaway that would happen in air

2. Dielectric elastomer actuator with oil capsules

To be portable together with the actuator, oil is encapsulated in a membrane capsule on each side of a pure-shear DEA, as shown in Fig. 2. The capsule has a soft membrane sealing oil in a cavity above the substrate of DEA. Build of this oil capsule is similar to that for tunable liquid lens[25, 26], but it is intended here to conform with the axial deformation of the activated DEA as shown in Fig. 2. Compliant electrodes on the

DEA are immobilized graphite flakes as shown in Fig. 3. Under oil immersion in the soft capsule, the immobilized graphite-flake can self clear in the event of pre-mature localized breakdown of the DEA and thus help the DEA sustain a higher electric field of operation.

Figure 2. Dielectric elastomer actuator with oil capsules: (a) schematic drawing for its sectional build. Upon electrical activation, the actuator elongates from an initial state in (b) and to the activated state in (c). Photographs of the actual prototypes in the front view (d) and side view (e) respectively.

Figure 3. Morphologies of very thin coating of graphite powders on a VHB substrate

Fabrication of this oil-capsule DEA was done manually with detailed steps described below. Substrate to the oil capsule is a DEA configured in the pure-shear condition. The DEA was prepared by equi-biaxially pre-stretching a dielectric elastomeric membrane (VHB4910) for 400% strain in the x direction and 400% strain in the y directions respectively. This pre-stretching yielded a pre-stretched membrane thickness of $40\mu\text{m}\pm 2\mu\text{m}$, as measured at 5 locations using a high-precision micrometer (Mitutoyo ID-C543). Subsequently, both sides of this pre-stretched membrane were brushed with very thin coatings of graphite flakes (Timcal TIMREX KS6 with $6\mu\text{m}$ average size) as compliant electrodes which have an area of 6cm wide by 1 cm long. To make cavity, a spacer layer of the frame shape was lay on the border of the DEA substrate before the cavity was sealed by a cover layer of another membrane (VHB9473PC of $250\mu\text{m}$ thick). These lay-up layers were bonded naturally by their adhesiveness. Next, a large portion of the oil was dispensed by syringe injection to the capsule cavity, bulging out the capsule membrane. The other side of the DEA is also protected by the same prepared oil capsule. In the final step of fabrication, two acrylic plates acting as the lateral clamps were adhesively bonded on the two axial ends of the oil-capsuled DEA before the laterally clamped DEA was cut and released from the rest of passive pre-stretched membrane. Completion of these fabrication steps yield an oil-capsule DEA, as shown in Fig. 2, under an axial pre-stress by a deadweight.

Silicone oil (Dow Corning Fluid 200 50cSt) is used here for quenching electrical arcing and thermal runaway. Such oil immersion helps DEAs better withstand partial discharge, as compared to air. Our previous study showed the oil-dipped DEA with graphite powder electrode is self-clearable from breakdown at very high field[17]. The graphite powders are adhered well (i.e. immobilized) as coating on the elastomeric substrate so that they do not flow. In contrast, carbon grease may flow and may cause electrical shorting through the punctured defective spot.

Silicone oil is commonly use to suspend conductive particles, e.g. in carbon grease that is commonly applied to form compliant electrode on VHB DEA[27, 28]. Due to its compatible use with VHB, silicone oil is not expected to compromise the mechanical and electrical strength of VHB elastomer. To verify this, effect of dielectric oil treatment on elastic modulus of VHB membrane is investigated here. A VHB sample was treated by 24-hour immersion in silicone oil bath before it was tested for mechanical properties, using a tensile tester. Fig. 4 shows the stress-strain curves for the samples with or without the oil treatment. It shows that silicone oil slightly softens the VHB membrane but do not limit the ultimate stretch. Indeed, the softening effect is still marginal over the small stretch range below 60% uniaxial strain.

As a benchmark, a dry DEA in air without oil capsules was also prepared. It was pre-stretched the same, and coated with the same graphite-powder electrodes as the oil-capsuled DEA. The dry DEA has a net weight ranging approximately 0.45–0.57 grams, which is lighter than the oil-capsuled one weighing 0.78–1.1 grams, excluding weights of the lateral clamps and a deadweight. The two types of DEAs, with or without oil capsule, are supposed to induce the same stress change at the same electric field. But

Figure 4. Effect of oil treatment on the axial modulus of a pristine VHB membrane, which is pre-stretched at the stretch ratios of $\lambda_{1p} = 5$, $\lambda_{2p} = 5$ in the x and y directions, respectively.

the oil capsules reinforce the DEA core and adds extra axial stiffness. Fig. 5 showed that the tensile stress required to uniaxially stretch the dry DEA is less than half that required to stretch the one with oil capsules

Figure 5. Effect of oil capsules on the axial modulus of DEAs, which are pre-stretched at the stretch ratios of $\lambda_{1p} = 5$, $\lambda_{2p} = 5$ in the x and y directions, respectively.

3. Electro-mechanical response

Actuation potential of DEA was previously estimated from its membrane properties, such as the dielectric strength, permittivity, and Young's modulus[1]. The realized work may, however, differ from the potential. In this case, actuation performance for the pure-shear DEA can be measured in terms of the free stroke under a constant deadweight (isotonic) or a blocked force when fixed in length (isometric), as shown in Fig. 6.

Figure 6. Schematics of the experimental setup for (a) isotonic and (b) isometric tests

3.1. Isotonic test

In an isotonic test as shown in Fig. 6(a), the dielectric elastomer actuator is pre-loaded by a constant dead weight P while being activated electrically to elongate and produce a stroke ΔL at the free end. The actuator elongation is caused by the Maxwell stress that reduces the internal pre-stress, which was initially in equilibrium with the constant pre-load. Hence, work done by the actuator can be measured as the product of the activated stroke at the free end and the constant pre-load P , like Ref. [29]. Hence, the maximum work density w_{max} realized is defined as the maximum work per actuator mass m ,

$$w_{max} = \frac{P \times \Delta L_{max}}{m},$$

where the maximum free stroke ΔL_{max} happens right before the breakdown voltage.

Under this isotonic test, both types of DEAs are pre-stretched axially the same, i.e. 5 times the initial un-stretched length, by a dead weight. Pre-stretching the oil-capsuled DEA requires a 422-gram deadweight, which is heavier than the 227 grams for the dry

one without reinforcement by capsule membranes. During the test, the samples of DEAs are activated with a voltage ramp, which increases stepwise until the breakdown voltage.

Fig. 7 compares actuation achievable by the two types of DEAs. The oil-capsuled DEA achieves a higher maximum actuation strain up to 61% at 22kV (equivalent to an electric field of 835MV/m). Fig. 8 shows deformation shapes of the oil-capsuled DEA under 22kV activation. The oil-capsule DEA can sustain 22kV without a breakdown, but it is not driven at higher voltage due to high field interference with the digital camera and computer system. On the other hand, the dry DEA in air is limited by electrical breakdown field up to 570MV/m at 16kV. Consequently, it produces a maximum actuation strain not more than 50%, even though it can generate more actuation strain at the lower field due its lower axial stiffness.

Figure 7. The isotonic strains induced as a function of the electric field for two types of DEAs, with and without oil capsules. Each type of DEA has three samples prepared and measured

It is observed that the dry DEA in air does not survive from localized breakdown. As it breaks down at 16kV, the leakage current surges high and the voltage falls low to nearly zero (see Fig. 9(a)). In addition, the breakdown is accompanied by wrinkling of dielectric elastomeric membrane and sparks tripping across the air near the edges of opposite electrodes (see Fig. 10). Eventually, a small puncture, which was caused by the electrically breakdown, spreads out to rupture laterally across the whole dielectric membrane, which was pre-stretched. This DEA breakdown is believed to be premature and attributed to air breakdown. On the other hand, the oil-encapsulated DEA survives the localized breakdown at an even higher electric field. Fig. 9(b) shows that current spikes at 17kV and 19kV are damped out by oil and do not cause permanent damage to the oil-encapsulated DEA substrate. In short, oil encapsulation helps quench electrical arcing and prevents thermal runaway from damaging the DEA.

Figure 8. Activation of an oil-capsuled DEA: (top) the initial state, (bottom) the activated state at 22kV (see supplementary Video)

Figure 9. Monitor of leakage current over a voltage ramp across: (a) a dry DEA in air; (b) a DEA with oil capsules.

Figure 10. Failure of a DEA in air starts with (a) wrinkling, (b) arcing across air, and (c) puncture before a complete rupture (see supplementary Video).

3.2. Isometric test

In an isometric test as shown in Fig. 6(b), the dielectric elastomer actuator is kept at a constant axial pre-stretch while being activated electrically to induce an axial force. During the activation, Maxwell stress Δt_3 is induced across thickness of the dielectric, following

$$\Delta t_3 = \frac{\epsilon_o \epsilon_r E^2}{2},$$

where E is the electric field. In turn, the induced Maxwell stress reduces the axial isometric pre-stress in the actuator membrane.

In this isometric test, the axial blocked force in the activated actuator is measured by a 10N-capacity load cell of a tensile tester (INSTRON 5569). To simulate the condition at the maximum isotonic free stroke, the actuator samples under test are pre-stretched 60% axially relative to the initial pre-stretched length. Before electromechanical testing, the pre-stretched elastomeric membrane is let fully stress relaxed. Subsequently, the actuator samples are subjected to a stepwise voltage ramp towards the maximum achievable voltages and its field-activated change in the blocked force is measured. Two types of DEAs, with or without oil capsule, were tested. The stress change is calculated as the force change over the DEA membrane thickness. The passive capsule membrane of the oil encapsulated DEA is not expected to influence the activated stress change, though it affects the initial pre-stress level.

Fig. 11 shows that the axial blocked force in the actuator membrane decreases with increasing voltage. The oil-capsuled DEA achieves a higher maximum force change up to 1.5N, 50% more than the 1N achieved by the dry one in air. It is noted that the dry DEA in air fails terminally at slightly above 9kV while the oil-capsule actuator sustains a higher voltage up to 16kV. Due to the constant axial length and vanishing pre-stress in the membrane, the oil-capsuled DEA wrinkles at 16kV as shown in Fig. 12.

This in turns cause unsteady force measurement at 16kV (see Fig. 11) even though the oil-capsule DEA has yet broken down electrically.

Fig. 13 shows that the induced stress change increases with increasing electric field. The trend of increasing stress change with increasing field is following that of the Maxwell stress, but the measured stress change is a lot lesser than the Maxwell stress beyond 150MV/m. The maximum stress change achieved by the oil-capsuled DEA is 1.05MPa at 16kV (i.e. 640MV/m field), while that achieved by the dry one in air is 0.60MPa at 9kV (i.e. 350MV/m field).

Figure 11. Axial blocked force in the DEAs, which are pre-stretched at a constant length by a tensile tester while electrically activated by stepwise increasing voltages

Figure 12. Wrinkling of the oil-capsule DEA at 16kV during isometric test

4. Discussions

Interestingly, the present findings showed that the pure-shear DEA with oil encapsulation can sustain a very high electric field, without succumbing to breakdown

Figure 13. The induced isometric stress change as a function of the electric field for two types of DEAs, with and without oil capsules. Each type of DEAs has three samples prepared and measured

by electromechanical instability. This indeed agrees with the theories that the pure-shear DEA, with the help of lateral clamping, could have survived electromechanical instability threshold [21, 22, 16, 23] if it did not succumbed to other failure modes in air. For comparison with experimental measurement, we establish here a similar theoretical model but using the current material parameters. In addition, performance of this oil-encapsulated DEA is compared with those reported for the DEAs in air.

Figure 14. Diagrams illustrating states of a DEA: (a) original state, (b) pre-stretched state, and (c) activated state

4.1. Comparison with theory

Here, we develop a theoretical model similar to that developed by Kollosche's[16] and Zhu's[23] to verify that the pure-shear DEA, which is laterally clamped and axially pre-loaded, can survive electromechanical instability. Subsequently, the theoretical prediction is compared with the measured actuator performance.

This model makes use of the Gent's hyper elastic material model to describe strain-stiffening effect in the highly stretched elastomer. According to Gent[30], the strain energy per unit volume W in the highly pre-stretched elastomer is given as:

$$W(\lambda_1, \lambda_2, \lambda_3) = \frac{-\mu J_{lim}}{2} \ln \left(1 - \frac{\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3}{J_{lim}} \right)$$

where, μ is shear modulus and J_{lim} is the stretch limit or the maximum value of $J_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3$. The stretch ratios λ_1 , λ_2 , and λ_3 are defined in three orthogonal directions with subscripts 1, 2, and 3 (as shown in Fig. 14). For incompressible elastomer, its volumetric product is a constant: $\lambda_1 \lambda_2 \lambda_3 = 1$.

According to Wissler *et al* [21], the principal Cauchy stresses or true stress t_i (force per sectional area) in the stretched elastomer can be determined from the derivative of the strain energy potential with respect to the stretch ratio λ_i :

$$t_i = \lambda_i \frac{\partial W(\lambda_1, \lambda_2, \lambda_3)}{\partial \lambda_i} - p, \quad i = 1, 2, 3$$

where the hydrostatic pressure p is determined by kinetic boundary conditions.

At its passive state as shown in Fig. 14(b), the elastomer membrane is subjected to an initial pre-stretches with λ_{1p} and λ_{2p} . The membrane is initially free from stress across its thickness H : $t_3 = 0$ (Fig. 12(a)), while it is pre-stretched axially for λ_{1p} by a deadweight $P = t_{1p}(L_2 \lambda_{2p} H / (\lambda_{1p} \lambda_{2p}))$. The initial pre-stresses t_{ip} in the membrane can be solved from the stress equilibrium equations above.

When activated by a voltage V across its thickness (Fig. 14(c)), the elastomer membrane is subjected to a compressive Maxwell stress, following:

$$t_3 = -\frac{1}{2} \epsilon_o \epsilon_r \left(\frac{V \lambda_1 \lambda_2}{H} \right)^2$$

with $\lambda_2 = \lambda_{2p}$ due to lateral clamping of the pure-shear condition. Solving the stress equations yields for the axial stretch ratio λ_1 . In turn, the axial isotonic strain can be determined as $s_1 = (\lambda_1 / \lambda_{1p} - 1)$.

When activated excessively to the extent that the lateral stress in the membrane vanishes $t_2 = 0$, the membrane is no more clamped laterally and its lateral stretch λ_2 is no more prescribed by λ_{2p} . Solving the stress equations then will yield for λ_1 and λ_2 .

The material parameters were obtained by least-square fitting the experimentally measured stress-strain curve, as shown in Fig. 6. They are found to be: $\mu = 60\text{kPa}$, $J_{lim} = 150$. The dielectric constant was taken to be $\epsilon_r = 4.7$ [18] for a pre-stretched VHB4910 membrane with 5 times its initial length.

Fig. 7 showed that the analytical prediction agrees well with the measured actuation strains under the isotonic test. The predicted actuation strain increases quadratically

with the increasing electric field when the lateral clamping remains effective. This quadratic trend is similar to most previous reports up to the point where the membrane pre-stress vanishes and DEAs often fail pre-maturely. However, theory showed that the isotonic actuation strain increases at a decreasing rate with respect to increasing electric field. Despite this tapered actuation, a breakdown by electromechanical instability did not happen even beyond the point of vanishing lateral pre-stress in the membrane. Hence, it is confirmed that the DEA under isotonic test does not necessarily fail by electromechanical instability. In the case for the isometric test, the induced axial stress change is predicted to be equal to the Maxwell stress and proportional to the field squared. However, at an electric field greater than 150MV/m, the measured axial isometric stress change is a lot lower than the predicted Maxwell stress (see Fig. 13). This deviation could be due to material property changes at the very higher field and deformation. Future work should further investigate the real causes to this deviation.

4.2. Comparison with other works

DEAs, which were configured in the pure-shear condition, differ in their reported performance of axial actuation. Their performances for isotonic and isometric tests are summarized in Table 1 and 2 respectively. Performances of these existing DEAs in air are generally limited by electrical breakdown fields not more than 300MV/m, even with lateral clamping. In this work, we showed that use of oil encapsulation and immobilized graphite electrodes prevents the DEA from electrical breakdown and helps it sustain a very high electrical breakdown field up to 835MV/m. In addition, it is found that the use of immobilized graphite electrode alone also helps the dry DEA in air achieve a very high electrical breakdown field up to 570MV/m, in comparison to the reported values for the DEAs with carbon grease electrodes[16]. This enhancement is due to the fact that the immobilized graphite powders do not electrically short easily at the breakdown spot, like the flowable carbon grease does.

Under isotonic tests, the dielectric elastomer actuators deliver work by elongation under electrical activation. Their reported work densities are summarized in Table 1. Previously, Meijer et al.[5] found that a DEA in air realized a 13.17J/kg work density over a work loop of 5% isotonic strain and 0.6MPa isometric stress. The maximum isotonic work density of DEA in air is improved by lateral clamping to approximately 20–25J/kg at 300MV/m[16]. This work further showed that the oil encapsulated DEA realizes a higher maximum work density up to 31.51J/kg at a higher electrical breakdown field of 835MV/m.

Table 2 lists the maximum isometric stress reported for the various DEAs, capable of axial actuation. Previous reports showed that the maximum axial isometric stress change is lesser than the maximum Maxwell stress at the same field[31]. In addition, pre-stretch level is found to limit the maximum electric field. In this work, we found that oil immersion helps the DEA sustain higher electric field and consequently produce more Maxwell stress. As a result, the oil-encapsulated DEA achieves a higher isometric stress

Table 1. Comparison among DEAs in terms of work density under isotonic test

References	Elastomers	Electrode materials	Prestretch ratio (x, y)	Electric field (MV/m)	Actuation strain (%)	Maxwell stress (MPa)	Work density (J/kg)
Meijer <i>et al</i> [5]	VHB 4910	Carbon grease	—	~170	5	(0.60) ^a	(13.17) ^a
Kollosche <i>et al</i> [16]	VHB 4905	Carbon grease	(5, 4)	~300	90	1.29	(~20-25) ^b
Current work	VHB 4910	Oil-capped graphite powder	(5, 5)	835	61	16.6	31.51
	VHB 4910	Graphite powder	(5, 5)	570	50	6.6	21.91

^a work over a loop with 5% strain and 0.6MPa isometric stress, according to Ref. [5]^b based on theoretical model and experimental results given by the author, Kollosche in Ref. [16]**Table 2.** Comparison among DEAs in terms of the maximum isometric stress change

References	Elastomers	Electrode materials	Prestretch ratio (x, y)	Electric field (MV/m)	Actuation strain (%)	Maxwell stress (MPa)	Isometric stress (MPa)
Pelrine <i>et al</i> [31]	VHB 4910	Carbon grease	(6, 5)	150	0	0.92	0.78
Kofod <i>et al</i> [18]	VHB 4910	Carbon grease	(5, 5)	163	0	1.1	0.8
Kovacs <i>et al</i> [2]	VHB 4910	Carbon grease	(3, 6.5)	95	0	0.38	0.18
Current work	VHB 4910	Oil-capped graphite powder	(5, 5)	640	0	8.3	1.05
	VHB 4910	Graphite powder	(5, 5)	350	0	2.4	0.6
Buchanan <i>et al</i> [4]	Human elbow flexors				—		0.8–1.2

change up to 1.05MPa at 640MV/m, which is 76.7% higher than 0.6MPa at 350MV/m for the dry one in air. This high isometric stress change is comparable to the stress change, i.e. 0.8–1.2MPa, generated by human flexor muscles during elbow flexion[4].

5. Conclusions

In this paper, we showed that use of oil encapsulation and self-clearable graphite electrodes helps damp out and stop localized breakdown, which would otherwise cause puncture and ultimate rupture to DEAs if not stopped. With oil encapsulation, the laterally clamped DEAs sustain a very high electrical breakdown strength up to 835 MV/m and realize a very high isotonic work density. Meanwhile, they produce very high maximum isometric stress change up to 1.05 MPa, comparable to that induced by human elbow flexors. In future, we shall embody the oil capsules in the rolled DEAs to make strong artificial muscles. With the capacity of muscles-like work and stress, the oil-capsule DEAs are anticipated to be useful for driving future human-like robots.

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