Silicone rubber for energy harvesting:
Material and process development and testing of
dielectric elastomers

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Silicone Elastomers World Summit 2018
27 - 28 November | Milan, Italy
Outline

- Overview of Fraunhofer Society and Fraunhofer ISC
- Rubber for energy harvesting: operating principle
- Research project: “DEGREEN”
  - Material development
  - Process development
  - Testing of dielectric elastomers
- Conclusion
The Fraunhofer Gesellschaft undertakes applied research of direct utility to private and public enterprise and of wide benefit to society.

25,327 staff

72 institutes and research units

Finance volume

2.3 billion

2.0 billion

Major infrastructure capital expenditure and defense research

Almost 30% is contributed by the German federal and states Governments

More than 70% is derived from contracts with industry and from publicly financed research projects.

2017
## Facts: Fraunhofer Institute for Silicate Research ISC

<table>
<thead>
<tr>
<th>Employees (2017)</th>
<th>480 employees (350 permanent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locations</td>
<td>5 locations: Würzburg</td>
</tr>
<tr>
<td></td>
<td>with approx. 10 000 m² lab and technical space</td>
</tr>
<tr>
<td>Centers</td>
<td>2 Application Centers: Aschaffenburg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Budget (2017):</th>
<th>35,2 Mio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invest</td>
<td>5,3 Mio</td>
</tr>
<tr>
<td>Contract venue (industry)</td>
<td>8,3 Mio</td>
</tr>
<tr>
<td>Project funding (nat.</td>
<td>internat.)</td>
</tr>
<tr>
<td>Public funding</td>
<td>8,6 Mio</td>
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SUBJECT: MATERIALS MEET...
...ENERGY
...RESOURCES
...BIOMEDICINE
...CLEAN ENVIRONMENT
...ADAPTIVE SYSTEMS

in Euro
Rubber for energy harvesting: operating principle
Using dielectric elastomers

- Dielectric elastomers consist of a very stretchable elastomer film (e.g. silicone, polyurethane), coated on both sides with highly stretchable electrodes (silicone rubber filled with carbon black, graphite, metal particles)
- Highly stretchable (up to 100 % elongation)
- Further applications of dielectric elastomers: actuator and mechanical sensor (pressure, strain)
Rubber for energy harvesting: operating principle
Using dielectric elastomers

- Transformation of mechanical energy into electrical energy inside the dielectric layer
- Continuous stretching and relaxing of the dielectric elastomer while applying a constant voltage
- Electrical net energy gain by changing the capacitance of the dielectric elastomer
- Converted energy for one cycle:

\[ \Delta W = \frac{1}{2} \Delta C \times U^2 \]

Research project: DEGREEEN
DEG for energy harvesting

- “DEGREEEN”: Use of Dielectric Elastomer Generators for Regenerative Energies
- Publicly funded by the Bavarian state
- Project term: 06/2012 – 05/2019
- Aim: development of energy converters based on dielectric elastomers for slow flowing waters
- The impact on landscapes, flow situations in rivers, restrictions of flora and fauna as well as noise nuisance have to be prevented as far as possible
Research project: DEGREEN
DEG for energy harvesting

- The electrical energy is to be used for environmentally-friendly decentralized energy supply of e.g. remote areas or for the recharge of electric vehicles in rural areas
- Kinetic energy: water flow of small rivers
- Transformation of kinetic energy into negative pressure by using a venturi nozzle → negative pressure strains the rubber film biaxial
Research project: DEGREE\nMaterial development

- Extreme mechanical and electrical requirements: no commercial silicone material with flexible processing parameters available
  → Development of specific silicone formulations and adaptation to the processing for multilayer films
- Different developments of silicone formulations for
  - the dielectric/protective layers
  - the conductive layers
- Good adhesion between the layers
Research project: DEGREEN
Material development

- Achieved dielectric properties:
  - High dielectric strength: 97,4 kV/mm
  - Adjusted elastic modulus: 1,2 MPa
  - Elongation at break > 300 %
  - Low processing viscosity 25 Pas @ 1 s⁻¹
  - High dielectric permittivity $\varepsilon_r > 3$
    (concepts available)
  - Good behavior during fatigue testing
  - Adjusted curing parameters
Research project: DEGREEN
Material development

- Achieved electrode properties:
  - Low specific resistance, even under strain (up to 100 %)
  - Low increase of resistance during fatigue testing
  - Adjusted viscosity for processing with rotary screen printing unit
  - Adjusted curing parameters

![Graph showing specific resistance vs. linear strain](image)
Research project: DEGREEN

Process development

- Modular roll to roll (R2R) unit for large scale production of thin multilayer films
  - Coating width up to 0.5 m
  - Cleanroom for high quality layers
- Slot die coating for dielectric layer
- Rotary screen printing for patterned electrode layer
Research project: DEGREEN
Process development

- Challenges in process development:
  - Stable multilayer coating process (Slot die and rotary screen printing)
  - Constant thickness of each layer
  - Purity of the dielectric layers (cleanroom and filtration)
  - Opaque and precise printing of the electrode layers
  - Precise winding and unwinding of the substrate
  - Electrostatic charge on top of the substrate
Research project: DEGREE
Process development

- Achieved multilayer properties:
  - Successfully coated 150 meters with almost 500 generator films
  - 11 layers processed: 5 electrode, 4 dielectric and 2 protective layers
    → 4 layers for converting energy in each rubber film!
  - Total thickness: 1.7 mm
  - Electric test with high voltage (un-stretched):
    10 kV
    → yield of 90 %!
## Research project: DEGREEN

**Testing of dielectric elastomers**

<table>
<thead>
<tr>
<th></th>
<th>Dielectric layer</th>
<th>Electrode layer (encapsulated)</th>
<th>Multilayer composite</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurand</strong></td>
<td>Mech. failure</td>
<td>Resistance + mech. failure</td>
<td>Capacitance + mech. failure</td>
</tr>
<tr>
<td><strong>Failure monitoring</strong></td>
<td>Ultrasonic sensor</td>
<td>Load cell</td>
<td>Ultrasonic sensor</td>
</tr>
<tr>
<td><strong>Strain cycles</strong></td>
<td>Biaxial</td>
<td>Linear</td>
<td>Biaxial</td>
</tr>
<tr>
<td><strong>Strain excitation</strong></td>
<td>Compressed air</td>
<td>Eccentric drive</td>
<td>8 cylinder drive</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>&lt; 1 Hz</td>
<td>5 Hz</td>
<td>1 – 5 Hz</td>
</tr>
</tbody>
</table>
Research project: DEGREEN
Testing of dielectric elastomers

- Electrode layer: 8 Load cells

- Electrode layer (encapsulated)
  - Resistance + mech. failure
  - Load cell
  - Linear
  - Eccentric drive
  - 5 Hz

- 8 samples
  - Linear strain

- Stress cycles vs. Resistance [Ohm]
  - Sample 1
  - Sample 2
  - Sample 3
  - Sample 4
  - Sample 7

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Research project: DEGREEN
Testing of dielectric elastomers

- Multilayer composite:

<table>
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Climatic chamber

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8 cylinder drive
Research project: DEGREEN
Testing of dielectric elastomers

- Multilayer composite - mechanical stability:
  - Surface enlargement: 100 %
  - Frequency: 1 Hz
  - C-measurement not implemented yet
  - 8 samples

→ Averaged cycles: at least 5 million cycles under biaxial load
→ No delamination!
Research project: DEGREEN
Testing of dielectric elastomers

Latest high voltage test:
- Using compressed air for biaxial strain
- 74 rubber films
- Test voltage: 4 kV

→ Harvested Energy per cycle: 15.5 J
Research project: DEGREE

Advantages

Advantages of using DEG:
- Minimum impact on environment: no dam and fish pass necessary
- Modular: adaptable to flow situation of small rivers
- Silent and self-sufficient system
- Continuous (24h/365d) and decentralized energy supply

Concept for 100 W unit
LxWxH: 2,0 x 2,6 x 1,4 m³
Research project: DEGREEN

Outlook

For higher energy output increase of …
- electric field
- conversion of water flow to negative air pressure

Converted energy for one cycle:

\[ \Delta W = \frac{1}{2} \cdot \Delta C \cdot U^2 \]
Conclusion

Feasibility study about using dielectric elastomers for energy harvesting:

- Material development:
  long-term stable mechanical and electrical properties
- Process development:
  high yield manufacturing process for complex multilayer system
- Testing of dielectric elastomers:
  high material fatigue of multilayer composite without delamination

→ Proven feasibility, further improvements must be made for commercialization

Interested?
We express our thanks to the Bavarian State Ministry of Economic Affairs, Energy and Technology for the funding provided!

Thank you for your attention!

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