Electronic Supplementary Material (ESI) for RSC Advances

Electronic Supplementary Information (ESI): *Variable stiffness material based on rigid low-melting-point-alloy-microstructures embedded in soft poly(dimethylsiloxane) (PDMS)*

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1 Thermal expansion

Heating of a material causes dimensional changes due to thermal expansion. For small temperature changes in isotropic materials, the thermal expansion is linear in all directions and can be represented by,

$$\varepsilon_{\mathrm{T}} = b_{\mathrm{L}}\Delta T, \tag{1}$$

where ε_{T} is the thermal strain, b_{L} is the linear coefficient of thermal expansion and ΔT is the change in temperature.[1] Using this relationship and the equation for resistance, $R = \rho L/A$, and assuming a constant material resistivity, ρ, we can determine the change in resistance due to thermal expansion,

$$\Delta R/R_0 = (1 + b_{\mathrm{L}}\Delta T)^{-1} - 1. \tag{2}$$

The thermal coefficient of expansion for the low-melting-point alloy (LMPA) is $b_{\mathrm{L}} = 25 \times 10^{-6}$ °C^{-1}.[2] For a temperature change of 22 °C (25 °C to melting at 47 °C), the thermal expansion of only the solid LMPA heating (not melting) would result in a resistance change of -0.55×10^{-3}. When the LMPA melts it experiences a linear expansion of at most 0.02%, which would cause a resistance change of approximately -0.2×10^{-3}.[2]

The volumetric coefficient of thermal expansion for the PDMS (Sylgard 184) is $b_{\mathrm{V}} = 9.6 \times 10^{-4}$ °C^{-1}.[3] For small temperature changes we can approximate the linear thermal expansion coefficient as $b_{\mathrm{L}} = b_{\mathrm{V}}/3 = 3.2 \times 10^{-4}$ °C^{-1}.[4] Then, for a 22 °C change in temperature, the thermal expansion of only the PDMS channel would result in a change in resistance of -6.99×10^{-3}. This is much higher than the resistance change from the thermal expansion of the LMPA only, but it is still much smaller than the resistance change observed from the change in resistivity of the LMPA as it melts ($\Delta R/R_0 = 0.47$) (see Thermal Behavior Section of the main article).

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2 Elastic modulus

The samples used for elastic modulus tests were fabricated in different ways depending on the material. The PDMS (Sylgard 184) samples were made by laser cutting (40W CO2 Deluxe Hobby Laser, Full Spectrum Laser) pieces of spare PDMS left over from the variable stiffness device fabrication (see Figure 1(a)). The LMPA (Cerrolow 117) samples were fabricated by casting molten alloy in a laser-cut polyester mold on top of a rubber sheet (see Figure 1(b)). The polyester mold was attached to the rubber using double-sided tape. Once cooled, the LMPA could be removed from the mold by peeling off the rubber layer.

Table 1 Data collected for samples of PDMS and LMPA used for testing the modulus of elasticity. Three samples of each type were tested. See Figure 1 for sample dimensions. Dimensions were measured by digital calipers.

Material	w/mm	h/mm	L/mm	Elastic modulus /MPa
PDMS	2.80±0.10	0.46±0.08	8.30±0.09	1.81±0.06
LMPA	0.58±0.01	0.32±0.01	6.15±0.18	3.00±0.13

The elastic moduli of the PDMS and LMPA were determined experimentally using the same set-up described for stretching experiments (see Experimental Section of the main article), as shown in Figure 1(d). Samples were clamped by their wide ends, and they were strained at a constant speed of 100 μm s^{-1}, which corresponds to strain rates of 0.016 s^{-1} and 0.012 s^{-1} for PDMS and LMPA samples, respectively. This speed is the same as was used in the bending and stretching tests performed on the variable stiffness devices. The elastic modulus was extracted from the linear portion of the stress-strain curves ($E = \sigma/\varepsilon$). For PDMS samples, the behavior was linear up to approximately 10% strain, and for LMPA samples linearity stopped near 1% strain. Table 1 provides a summary of the results from experiments on three samples of each type of material. The modulus of the LMPA is found to be 3 GPa, and that of the PDMS is 1.81 MPa. The modulus of the PDMS is very close to values reported by Schneider *et al.* of 1.82 MPa.[5] The measured modulus of the LMPA may be lower than the actual modulus as a result of defects in the LMPA samples. This is because, when manufacturing the LMPA test samples, it is very difficult to prevent some air bubbles from getting trapped in the molten alloy.

References

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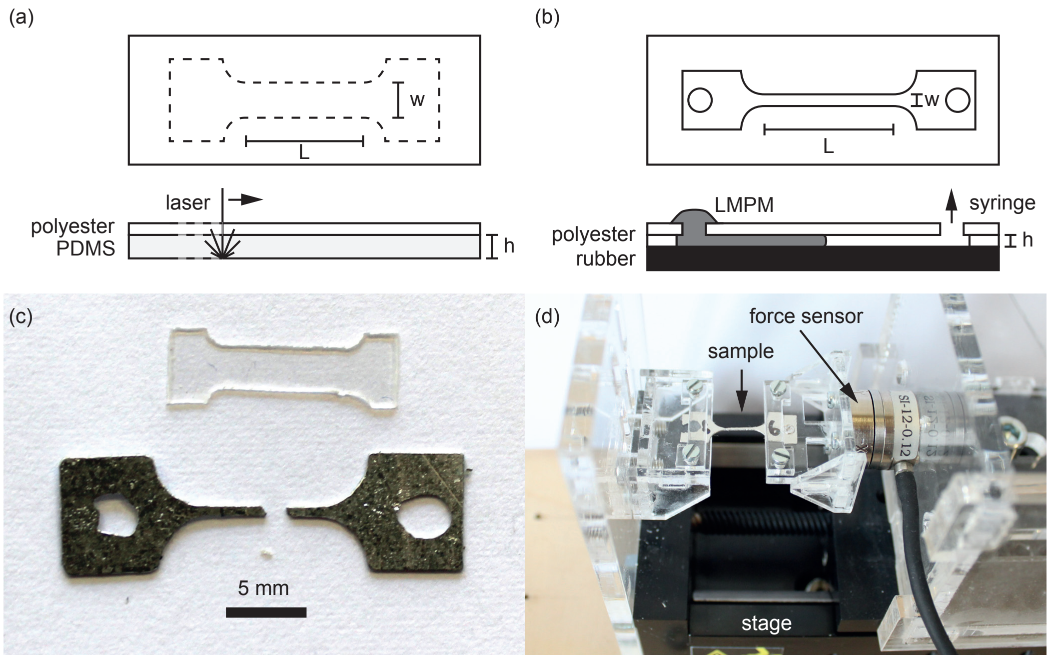

Fig. 1 (a) Top- and side-view drawings of PDMS samples for modulus testing being created by laser cutting. (b) Top- and side-view drawings of LMPA samples for modulus testing being created by casting of molten LMPA. (c) Photographs of PDMS (top) and LMPA (bottom) samples. The LMPA sample is broken in the middle from modulus testing. (d) Photograph of test setup, showing a LMPA sample clamped between acrylic plates attached to a force sensor and a fixed support. The stage is used to apply strain to the samples.