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Smart Morphable Surfaces for Aerodynamic Drag Control

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Smart Morphable Surfaces for Aerodynamic Drag Control

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Fabrication Protocol. Our Smart Morphable Surfaces (Smorphs) were fabricated using rapid digital prototyping tools, to obtain samples with a range of material and geometric properties.

In Table S1, we list the details and curing protocol of the silicone-based rubbers used for both coating and casting of our samples: Polydimethylsiloxane (PDMS), Ecoflex and Vinylpolysiloxane (VPS). Combined, these elastomers allowed us to explore a wide range of elastic moduli for both the outer stiff-shell, E_f , and the soft-core, E_s , within the range $9 \lesssim E_f/E_s \lesssim 162$. Using PDMS (Sylgard 184, Dow Corning) has the added advantage that its elastic modulus can be tuned in the range 10^4 - 10^6 Pa, which can be accomplished by varying the relative ratio between the base and curing agents^[30]. Curing of the PDMS components was performed in a convection oven at the relatively low temperature of 40°C, which ensured minimum levels of thermal expansion of the mold. The sample components made with Ecoflex and VPS were cured at room temperature, 20°C. Given that the thickness of the outer

stiff shell produced through coating (more details below) depends on the curing speed, we accelerated the curing process by making use of an accelerator that was mixed to the PDMS elastomer in the weight proportion 5:1 (PDMS Base:Cure Accelerator).

To measure the elastic modulus of the elastomers that we used (PDMS, VPS and Ecoflex), we cast cylindrical specimens (2cm in height and 2.6cm in diameter) out of these materials. The cylinders were then tested under uniaxial compression using a Zwick material testing machine. Assuming a linear elastic model, the Young's modulus was measured from the slope of the acquired stress-strain curves. We point out that barreling of the cylindrical sample occurred under compression due to the geometry of our test. As such, and following a standard protocol^[31], a correction factor on the Young modulus measured directly from the experiments had to be taken into account.

<i>Material</i>	<i>Material Reference Name</i>	<i>Providing Company</i>	<i>Base/Cure ratio (in weight)</i>	<i>Curing temperature [°C]</i>	<i>Curing time [hours]</i>
PDMS (Polydimethylsiloxane)	Sylgard 184	Dow Corning, Inc.	10:1	40°C (with Cure Accel.)	5h (with Cure Accel.)
PDMS (Polydimethylsiloxane)	Sylgard 184	Dow Corning, Inc.	50:1	40°C (with Cure Accel.)	5h (with Cure Accel.)
Cure Accelerator for PDMS	3-6559 Cure Accelerator	Dow Corning, Inc.	5:1	n/a	n/a
Ecoflex	Ecoflex 0010	Smooth-On, Inc.	1:1	Room temperature ~20°C	24h
VPS (Vinylpolysiloxane)	Elite Double 8	Zhermack Inc.	1:1	Room temperature ~20°C	30 min

Table S1. Material details, preparation and curing protocol for the elastomeric materials used to fabricate our Smorphs samples.

In Figure S1a-c, we present a schematic diagram of the multistep process employed to fabricate the hemispherical Smorphs, each of which is a three-level system comprising of: i) a thin-stiff outer shell, ii) bounded to a softer substrate core that iii) containing an under-surface cavity. The fabrication protocol consisted of the following three steps – A) Coating of the thin-stiff outer shell, B) Casting of the soft foundation and C) Demolding of the sample – the details of which are discussed next.

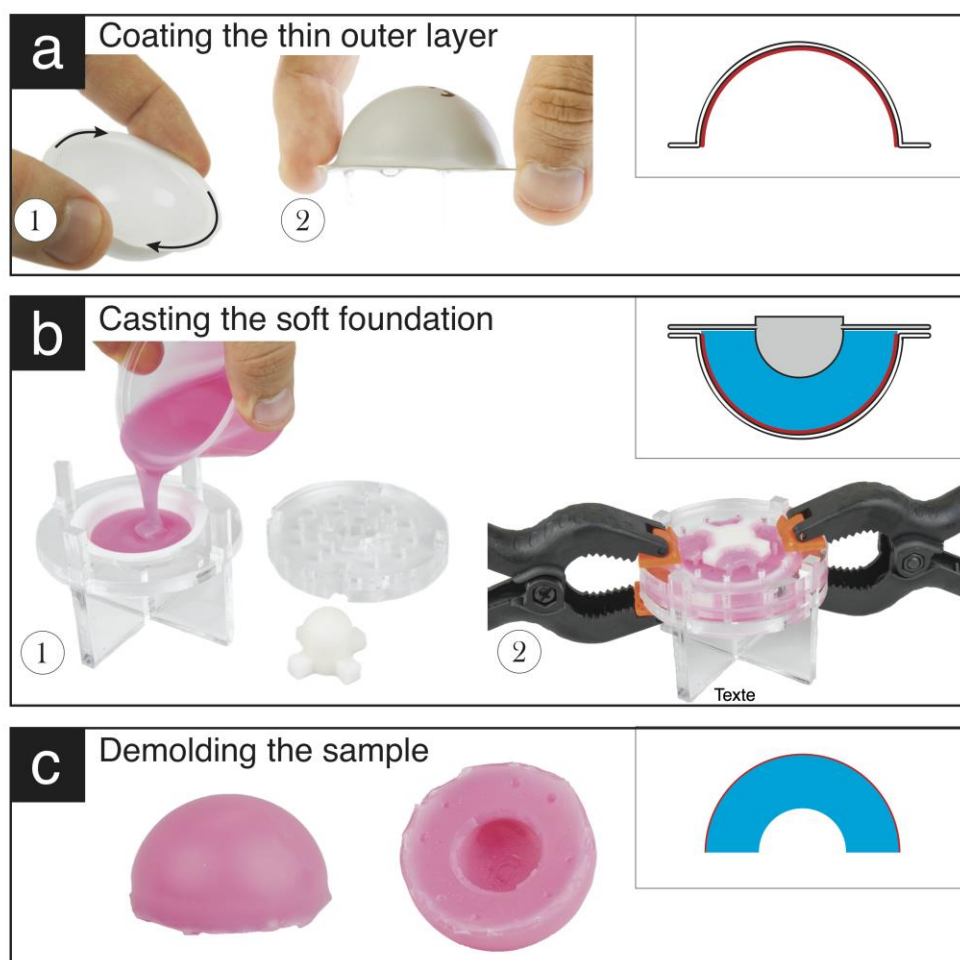


Figure S1. Multistep protocol for the fabrication of Smorphs. a, Coating of the thin-stiff outer layer. **b,** Casting of the inner soft substrate. **c,** Demolding the sample.

A) *Coating of the thin-stiff outer shell:* One of the main challenges of our fabrication procedure was ensuring that the outer thin shells had a customizable constant thickness (in the range $20 < h[\mu\text{m}] < 1000$) and as free of imperfections as possible. This issue was circumnavigated through rapid prototyping followed by a coating method. First, we created hemispherical molds by hot vacuum-forming Polystyrene sheets (Altec Plastics) with the desired radius of curvature. Each mold was then fully coated with the elastomer mixture of PDMS (10:1) and cure accelerator (5:1), prior to curing (Figure S1a). After the polymer was poured into the spherical mold, the ensemble was then rotated by hand to ensure that the entire surface of the mold was fully wet. The molds were then turned upside-down, in order for the excess of the mixture to drain under gravity, while curing in an oven for 5 hours at 40°C . A balance between gravity, viscosity, surface tension and polymerization rate resulted in thin shells with the remarkable constant (to within 10%) thickness of $h \sim 100$. The coating-curing process was repeated multiple times if thicker shells were desired, up to $h \sim 1\text{mm}$. Note that if the curing was accelerated (e.g. by adding the cure accelerator agent), this resulted in thicker coating layers and, therefore, thicker shells. Given that we chose to use a low curing temperature to avoid any thermal expansion of the molds, an appropriate mixture of PDMS and cure accelerator (proportion 5:1 in weight – PDMS Base:Cure Accelerator 3-6559 from Dow Corning, Inc) had to be used to speed up curing, thereby achieving the targeted thicknesses. This coating process is analogous to the Landau-Levich problem for the coating of fibers and plates^[29], although a formal rationalization of the process in this curved geometry has, to date, not yet been performed. We therefore use this coating method empirically, knowing which parameters are necessary to target our desired shell thicknesses.

B) *Casting of the soft foundation:* Once the outer thin shell was cured, either VPS or Ecoflex was poured into the mold to produce the softer core. More precisely, acrylic

scaffolding was laser-cut to hold the styrene mold horizontally (Figure S1b). As soon as the elastomer is poured, the mold was covered with an acrylic disk containing a hole, onto which we attached a rigid 3D-printed part that produced the under-surface cavity.

C) Demolding of the sample: Once the elastomeric soft-core was completely cured, the final sample could then be carefully demolded (Figure S1c). Since we observed that the elastomers continued to cure and slowly change their elastic properties for a few days after fabrication, samples were stored in a ventilated area for seven days prior to any experiments being performed.

Surface Profilometry of samples through 3D Laser scanning. The three-dimensional surface topography of our depressurized Smorphs were digitized using a Desktop 3D Laser Scanner (NextEngine). These digital profiles of each of the dimpled wrinkling patterns were image-processed using software developed in-house (based on Matlab, MathWorks, Inc). This way, we were able to identify the location of each dimple, including the position of their local minimum (see Figure S2a), as well as the surrounding crest that defines its edge/boundary (see Figure S2b). The image analysis started with the fitting of a spherical cap to the dimpled surface to find a mid-spherical surface (represented by the solid line in the inset of Figure S2b). We then measured the distance from the minimum (lowest point) of each dimple to the fitted mid-sphere, which defines half of the dimple depth, k . The wavelength of the pattern was measured from the distance between two neighboring dimples. The average and standard deviation were calculated from the measured data from all the identified dimples on the surface of the digitized Smorphs.

Wind Tunnel testing. Two hemispherical Smorphs samples were fabricated following the protocol described above and assembled around a rigid 3D printed annular mount, using

vacuum grease to avoid any air leakage. As shown in Figure S1c of the manuscript, the mounted Smorphs are supported by a stainless-steel hollow pipe, which, itself, passes through an air bearing and attaches to a precision force sensor. This force sensor is used to measure the drag force, F_D , under aerodynamic loading. A T-junction between the supporting pipe and the load cell connects the sample to a vacuum pump, allowing for depressurization; a pressure differential, ΔP , is set between the inside and the outside of the cavity. The main body of the load cell is then covered with a polystyrene windshield to protect the instruments from any disturbance caused by the flow.

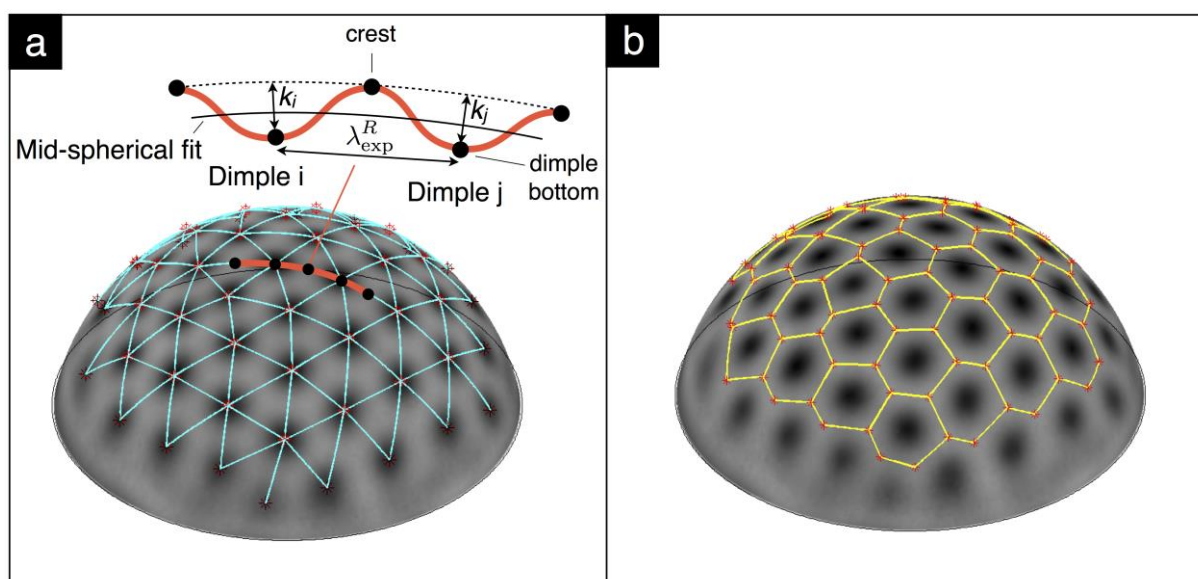


Figure S2. Representative three-dimensional scan of the surface morphology. **a**, Gray scale map of the radial coordinate of the surface with respect to the mid-surface position. Detection of the dimples (circles) using our image-processing algorithm; triangulation between nearest neighbors is highlighted by the blue lines; (Inset) Schematic of the measurements of dimple depth and wavelength. **b**, The crests surrounding each dimple are highlighted by yellow lines.

The fluid flow (directed from left-to-right on Figure 1c of the manuscript), is characterized by the Reynolds number, $Re = (\rho_a UD) / \mu_a$, where ρ_a and μ_a are the density and dynamic viscosity of air, respectively, U is the mean flow speed (measured with a Pitot tube) and D is the diameter of the sample. The Reynolds number of our experiments is typically in the range $10^4 < Re < 10^6$.

The experimental protocol to quantify the drag coefficient of the Smorphs, C_D , as a function of the Reynolds number (Figure 3a of the original manuscript), is as follows. The samples were first depressurized to the desired value of, ΔP , and the roughness of the resulting topography was characterized using the 3D laser scanner (mentioned above). Simultaneously, a digital photograph of the Smorphs was also taken from its side (e.g. as in Figure 1b, bottom, of the manuscript) to quantify any possible variation of the cross section of the sample during depressurization, which was taken into account for the calculation of C_D . The wind tunnel is then switched on and the drag force, F_D , measured for increasing values of the Reynolds number. For the measurements displayed in Figure 3b of the original manuscript, the sample was first initiated in its smooth state (no depressurization) and the flow speed was then set, to target a specific value of the Reynolds number. Finally, the drag force was measured for different values of ΔP .