Swimming through shell buckling

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Abstract

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THIS IS THE DEDICATION.

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75mm The Secret of Happiness lies in looking at all the wonders of the world

and never forgetting the two drops of oil in the spoon.

The alchemist, Paulo Coelho

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Materials and methods

0.1 SHELL FABRICATION

0.1.1 MOTIVATIONS

This study requires a full control over the geometry, the material and the manufacturing process to ensure the reproducibility of the experiments.

Further more, two constraints were to take into account: the ability to induce the buckling

within a pressure range of -1 bar and 1 bar and the ability to apply several cycles without damaging the shell.

This implies that the material to be used needs to have a high tensile strength to withstand the deformation cycle without entering the plastic domain and a rigidity small enough to trigger a buckling in the imposed pressure range and a feasible $(\frac{d}{R})$ range i.e $d > 1mm$ and $R < 50mm$. Visco-elastic polymers called elastomers qualify to these prerequisites and have been chosen for the shell manufacturing.

Before deciding to manufacture spherical hollow shells, we tried different kind of commercial ""balls"". It was not conclusive because the process of fabrication was not intended to be reproducible in terms of material composition, thickness or diameter. This is why it was decided to manufacture them.

Several techniques were considered to manufacture polymer-based spherical hollow shells, including 3D-printing, rotational molding, processes involving high-pressure vulcanization. These techniques would have required either buying expensive equipments or subcontracting to a company with inconveniences of time delay, loss of control over the process and expensive cost of prototyping. The most suitable solution was the more common bi-molding process where the two halves of an object are cast and then assembled. The main advantages being the cost and the low-time consumption, plus a total control over the process, which includes the choice of materials, the reproducibility and more freedom over the geometry.

Female mold: It consists of a cylinder of radius $R_{cylinder} = 30mm$ hollowed out to produce a half

a sphere imprint of radius $R_{out} = 25mm$ and a height of $h = 30mm$ (see fig.1). The concavity is

where the casting material is poured. A groove was added to store any potential material surplus.

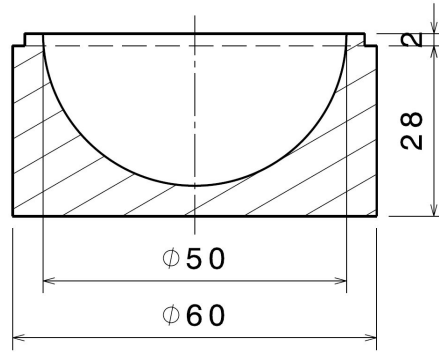Two female molds are necessary for the casting operation.

Figure 1: Longitudinal section of the female mold

Translation guide sleeve: It is a hollow cylinder with an inner radius $R_{in} = R_{cylinder} = 30mm$,

and a thickness of $5mm$. where the female mold is slid in. It is slightly higher than the female mold

by $5mm$. One extremity is provided with an inner chamfer of 5 which ensures the concentricity be-

tween the female mold and the male mold.

Male mold: Figure 3 shows the design of the male mold which consists of half a sphere of radius

$R_{int} < R_{out}$, which is changed to cast different thicknesses. It is supplied with a shouldering which

acts as a travel stop, its flanks have a slight angle of 5 providing a translation guide and preventing
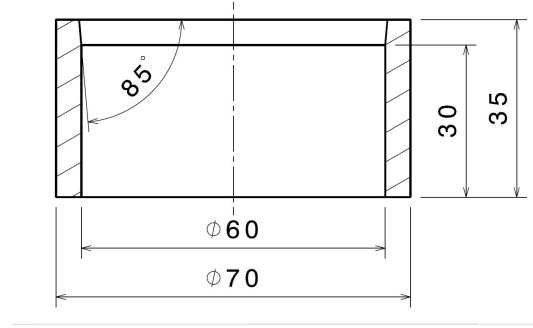
Figure 2: longitudinal section of the sleeve

an over-center locking in combination with the guiding sleeve previously presented. The cylindrical part over the shouldering helps manipulating the mold during the casting process. Three radii have been used: $R_{int} = 18.5mm, 20mm, 23mm.$ *
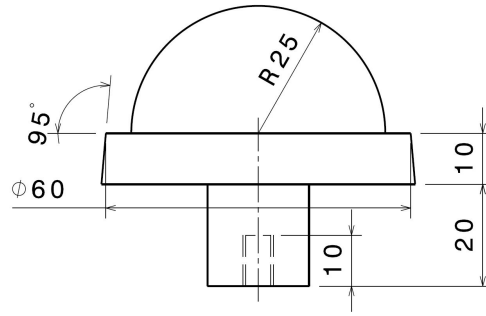

Figure 3: longitudinal section of the male mold

Gluing sleeve   It is a hollow cylinder with an inner radius $R_{in} = R_{cylinder} = 30mm$, a thickness of $5mm$ and a height of $50mm$. It is used during the gluing process to ensure the concentricity of the

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*All the molding parts presented are made of Aluminum "'Fortal'". The female and male molds were machined using a CNC (computerized numerical control) machine and with a precision of $tol = \pm0.01mm$. The surface roughness obtained was of $R_a = 0.04$ which indicates a very good finishing. This choice of manufacturing was unavoidable since no other alternative could produce spherical shapes with such precision conditions.

two halves of the sphere contained in the female molds which face each other.

Mechanical press   It's a simple press consisting of two metallic plates supplied with a set of threaded rods and hexagonal nuts used to apply pressure over female/male molds during the casting step to prevent bubbles from appearing during the casting step. It is also used during the gluing step on the female/female molds to ensure the contact between the two half spheres to be glued together.

Pasta machine   This machine (fig4) consists on two rotating cylinders, with an adjustable inter-space which allows to produce layers with the desired thickness.

Figure 4: Pasta maker

0.1.3 Materials and protocols

Three materials were used in the experiments done during the study: "'Dragon Skin®30'" which has a specific molding protocol and AJO 121 and AJO 122 which have a common molding protocol.

Dragon skin®30

This material is typically used to make special effects.In the case of our study, it was used to investigate the effect of the $\frac{d}{R}$ on the swimming mechanism. Its exact chemical constitution is not known, but what can be said is that it is cure liquid silicone compound, which consists of two liquid components named A and B. Component A represents the silicon polymer chains with eventually the presence of fillers to enhance its mechanical properties. Component B is the cross-linking agent providing bonds that link one polymer chain to another, decreasing the flexibility of the polymer chain and increasing its rigidity. Mixing these two components at room temperature, it creates a solid that takes the shape of the container it was poured in. The typical mechanical properties of the resulting rubber are:

- Shore A Hardness : 30

- Specific gravity : 1.08

- 100% elastic modulus : 0.6 MPa

- Elongation at break : 364%

- cure time (at room temperature) : 16 hours

1. Begin by determining the mass of a shell with a outer radius of $R_{out} = 50mm$ and a thickness *th* which gives an internal radius $R_{int} = R_{out} - th$, The mass[†] of a hollow sphere is given by the following formula:

$$Mass_{shell} = \frac{4\pi}{3}\varrho_{material}(R_{out}^3 - R_{int}^3)$$

2. In a beaker, we weigh 50% of the shell mass of component A which is the silicon polymer chain. We stir thoroughly and add 50% of the shell mass of component B, which constitutes the cross-linking agent, we stir thoroughly.

3. The mixture is then degassed thanks to a vacuum pump.

4. The female and male are cleaned using acetone and 50% of the degassed mixture is poured in the two female molds.

5. We degas again to make sure no air was entrapped during the previous step.

6. Each female mold is slid in the translation guide sleeve and the male mold corresponding to the desired R_{int} is gently slid inside the female mold to prevent air from getting trapped.

7. The female-male molds assembly is then pressed and locked using the press.[‡]

8. The press is then put into an oven at 65°C to speed up the cross-linking process reducing it from 16 hours to only 20 minutes.

HALF SPHERES GLUING   Once the two halves of a hollow sphere of the desired R_{int} are cast. We need to glue the two halves together to obtain a complete hollow sphere of thickness *th*. This part is critical: if the sewing is weak, it will tear apart during the buckling phase. if the sewing is thick, it

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[†]In practice, this mass is increased by 50% to take into account the eventual loss during the preparation.
[‡]This step is necessary to ensure that no bubbles get trapped during the assembly.

means that the shape is no longer spherical. If the gluing material is not the same, we lose the homogeneity of the material and potentially create a weak zone at the sewing, which would accelerate the weakening of this zone and ultimately tear apart.

To efficiently glue the two halves and avoid the problems stated previously. We used the same material to perform the gluing, but for that it was necessary to decrease the viscosity of the mixture and enhance its wetting properties. For this purpose, we mixed "'Pentane'" which is an organic solvent[1] with a solubility parameter similar to that of PDMS. The following describes the protocol of gluing:

1. Prepare 10g of a mixture A+B of the Dragon skin®30 and degas it.

2. Add 5 ml of "'Pentane'" to the mixture and stir to obtain a diluted mixture that is neither too liquid nor too viscous and pump the resulting liquid inside a syringe.

3. Use an abrasive such as sandpaper over the gluing area of the two halves casts to make the surface rougher.

4. Put back each cast in the female mold and align it correctly so that the gluing area is horizontal.

5. Pour uniformly a layer of the diluted mixture using the syringe needle on the gluing area of both casts.

6. Put one female mold inside the gluing sleeve, facing upward then slide the second one facing downward until the two gluing areas are in contact.

7. Ensure the contact by using the mechanical press and let the cross-linking happen at room temperature for 16 hours.§

8. After the curing time, remove the residual thin skin circling around the sewing area.

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§This time we don't use the oven to ensure that the pressure inside the spherical hollow shell is the atmospheric pressure.

AJO121/122

The two remaining materials *AJO 121* and *AJO 122* were samples kindly supplied by "'BLUESTAR silicones©'".Both are hot curing silicone rubbers after addition of a vulcanization agent. The typical applications of these materials are: molding and injection molding process for technical parts (sealing gaskets,grommets), extrusion profiles (windows profiles, sleeves, tubes) and calendering operations for manufactured hoses. They were chosen to investigate the effect of solid dissipation characterized by the rebound resilience property. This pair of materials present the particularity of sharing the same elastic energy storage capacity characterized by the elastic modulus.In the case of the samples provided by "'BLUESTAR silicones©'", both material present a soft white paste-like texture. The exact chemical composition of the pastes were not disclosed but what we know is that the curing agent, which is 1.25 % of 2,4-dichlorobenzoyl peroxide, was already mixed with the silicone polymer. The vulcanization process is temperature-controlled and is induced at 115°C.

The typical mechanical properties of the resulting rubbers are:

- 100% elastic modulus AJO121 / AJO122 : 2.2 MPa / 2.3 MPa

- Rebound resilience AJO121 / AJO122 : 45% / 65%

- Shore A AJO121 / AJO122 : 60 / 59

- Specific gravity : 1.16

- Elongation at break AJO121 / AJO122 : 560% / 366%

- cure time (at 115°C) : 10 minutes

1. Begin by determining the mass of a shell with a outer radius of $R_{out} = 50mm$ and a thickness th which gives an internal radius $R_{int} = R_{out} - th$, The mass of a hollow sphere is given by the following formula:

$$Mass_{shell} = \frac{4\pi}{3}\varsigma_{material}(R_{out}^3 - R_{int}^3)$$

2. Weight the calculated mass from the paste and divide it in two equal parts.

3. Press each part at the center of the female mold.

4. Each female mold is slid in the translation guide sleeve and the male mold corresponding to the desired R_{int} is slid inside the female mold.

5. The female-male molds assembly is then pressed and locked using the press.

6. The press is then put into an oven at 115°C to trigger the vulcanization process, during 8 minutes [¶].

7. A post-curing at 200°C is needed to optimize the mechanical properties of the material, to evaporate remaining volatile substances (sub-products linked to the peroxide) and allow the sublimation of the 2,4 Dichlorobenzoic acid which manifests as a white powder at the surface of the material, at the end of the previous step.

HALF SPHERES GLUING   The gluing using the AJO materials was very challenging for different reasons. First, the paste-like nature of the material which was not soluble in any organic solvent without compromising the vulcanization agent already mixed with the raw polymer. It also made manipulating it harder, contrary to the liquid nature of the "Dragon Skin®30"'. Second, we were not able to glue together two flat surfaces, due to the fact that the cross-linking process reached a

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[¶]This period was reduced to 8 minutes instead of 10 minutes to avoid reaching the maximum of the cross-linking, in order to complete the gluing

maximum with the prescribed time and temperature and no biding was possible afterward. This is the protocol followed which solved partially the problems previously stated:

1. Prepare two thin layers (0.1 mm) using the ""pasta maker"" machine. Adjust their width to 10 mm and the length to $2\pi R_{out} \approx 157mm$.

2. Use an abrasive such as sandpaper over the gluing area of the two halves casts to make the surface rougher.

3. Put back one cast in the female mold and align it correctly so that the gluing area is horizontal.

4. Put uniformly a first layer on the gluing area of one cast and make sure it adhered to the surface, cut the residual width using a scalpel.

5. Connect the remaining half (without the female mold) with the first and press to get and adhesion.

6. Put one female mold inside the gluing sleeve, facing upward then slide the second one facing downward until the two gluing areas are in contact.

7. Remove the female mold gently and roll the second layer around the sewing perimeter, taking care not to disconnect the two halves while doing so.

8. Encapsulate the shell inside the two female molds and exert pressure using the mechanical press.

9. Put the press inside the oven at 115°C for 10 minutes. Remove it and let it cool at room temperature.‖

‖The capsules produced using this protocol have an internal pressure close to 75% of the atmospheric pressure.

Molding protocol for Dragon skin®30

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Some extra stuff

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[1] Lee, J. N., Park, C., & Whitesides, G. M. (2003).   Solvent compatibility of
     poly(dimethylsiloxane)-based microfluidic devices. *Analytical Chemistry*, 75(23), 6544–6554.

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