Preprint of a paper sent to J. Microsc. on April 17th, 2006

Advanced fullerene-type texture and further features of the macadamia "nut"-shell as revealed by optical 3D microscopy

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Keywords. Advanced fullerene-type texture, bijective illumination, bionics, cracking, fracture toughness, germination, image composition, impact compliance, macadamia seed, surface texture, surface reconstruction, surjective illumination, three-dimensional optical microscopy, wooden shell microstructure.

Summary

Unlike previous assumptions, the hardshell part of the wooden macadamia "nutshell" is only 0.16 mm deep. Therefore, it must exhibit a special construction principle, because this seed is extremely tough towards being cracked. Bionic studies are undertaken with the aim to reveal the interesting as yet undetected construction principle that is suggestive for the solution of engineering problems. New optical three-dimensional digital microscopy with symmetric or asymmetric frontal ring illumination and with composition of images at equidistant focus also for surface reconstruction is used for the study of various qualities of the large and rough macadamia "nut" (botanically precise: seed) at various levels of magnification. The almost spherical object with two off-axis poles has an unreported advanced fullerene-like surface structure (consisting of pentagons and hexagons with additional small columnar stiffeners) at its wooden outer shell that makes the "nut" extremely resistant against cracking, but also permits the cracking by internal pressure for germination. The structure of the wooden shell is microscopically investigated from whole "nuts", cracked particles with sharp rectangular edges and from the depth of fissures. A thin hardshell (160 µm) is connected to softer wood (chewable; depth: 1.5 – 5 mm in the same seed) followed by insulating black (northern hemisphere) and white (southern hemisphere) glossy layers. One of the poles (northern) is fibrous and a very long channel down to the black layer could be imaged. The development of cracks starts from the poles (upon external or internal pressure) and from particular lighter coloured sites lacking the stiffeners in the fullerene-type structure that are imaged with full depth of focus by the versatile microscopic technique with high contrast. Additional features are hitherto unreported distinct red and green areas on and within the shell that are stable to air and light.

Introduction

What is generally called macadamia "nuts" are the hardshell seeds that must be cracked by particular patented "nutcrackers" with long handles (for example from Kenkel Inc. at http://www.kenkelnutcracker.com/) or with special anvil and impactor (W. M. Price, US Pat.

4520719 A, 1985) to obtain the edible kernels of the macadamia fruits. For scientific reasons we will deviate from the common usage and call the “nuts” botanically correct hardshell “seeds” from now on. They are very hard to crack with fracture toughness comparable with that of glass and many ceramics, and their specific work of fracture is about an order of magnitude higher than that of high quality structural ceramics (Jennings & MacMillan, 1986). This is of high importance for the undamaged isolation of the kernels and also for the industrial charring at high temperatures producing useful micropores (Jennings & MacMillan, 1986), but still hardly understood. Advanced optical microscopy should be helpful in that respect. The major possibilities of digital optical microscopy are unlimited depth of focus, frontal illumination, and three-dimensional (3D) imaging by composition of various images that are taken at equidistant focus. They allow for direct investigation of the opaque spherical seed shell by surface reconstruction, rather than requiring microtomes or polished cross-sections for 2D imaging. The advanced studies with light microscopy reveal new textures and differentiate local colour differences that are not available to scanning force techniques or electron microscopy. As very rough cracked shells can also be imaged with high focal depth, further structural details of the wooden shell become available and it is thus possible to understand why this seed has its extraordinary fracture toughness while it is still able to germinate.

Materials and methods

Microscopes

A Zeiss standard microscope with 3.2x and 10x lenses and 10x ocular with a tube for fixing a camera was used for sidewise illumination from a parabolic reflector white source. The digital microscope of Keyence Ltd. model VHX – 100K with almost frontal symmetric (surjective) and almost frontal asymmetric (bijective) illumination through optical fibres and ring lenses was used with the zoom-lenses VH-Z500 (500x – 5000x with respect to a 15 inch monitor) and VH-Z25 (25x – 175x). A digital camera recorded the light of a halogen lamp that was reflected by the sample in ambient atmosphere and sent the signals through optical fibre for digital imaging. Shadowing with enhanced contrast was obtained at slopes and by use of the asymmetric illumination by light extinction or attenuation from one side. The appearance of colours could be optimised by the settings of light intensity and contrast. 3D surface reconstruction was performed using the commercial technique of Keyence by collecting equidistant focal images and composing them electronically while change of position could be automatically corrected. The composite image was automatically generated only from in-focus areas

Macadamia seeds

Ripe almost spherical Macadamia ternifolia “seeds” with diameters of 24 – 25 mm shall for practical reasons have their north pole at the point of attachment to the tree (through the former fruit with an additional rather hard green shell as the pericarp that is not investigated here) and the south pole with a small white occlusion that is, however, displaced from the geometric pole by about 30°, making one way shorter between the so named “poles”. These seeds were collected from the ground under some trees by courtesy of the Mauna Loa Macadamia Factory Corp., Hilo, Hawaii 96720, USA, and the green pericarp husked if necessary. The hardshell was preliminary visualized after washing the “seeds” with water and air-drying. The structural features became more pronounced after de-waxing by submerging in a commercial neutral surfactant bath for cleaning dishes with some agitation followed by thorough rinse with water, when the "seeds" assumed a dark brown colour that turned back to light brown within about 2 h in ambient air. Drops of water did not wet the surface before and after such treatment. Similar behaviour and images were obtained with macadamia seeds as purchased from Kini Po-Po Creations Hilo, Hawaii 96720, USA, but these were smaller with diameters of 17 - 19 mm. The cracking of the larger brands was performed at a vice that was equipped with hard-steel claws.

Results

3D Microscopy
The larger scale features

Visual inspection of the water-cleaned or of the de-waxed seeds reveals their brown colour and some small lighter-brown regions. There is always one groove starting from the south pole that builds a meridian and varies individually in depth and width. It sometimes extends up to the north pole, but it turns more often into a ridge at latitude of about –30°. Some of the collected air-dried macadamia seeds without pericarp had beginning cracks, probably due to soaking water from wet ground sites with build-up of internal pressure (similar short cracks might also occur upon technical drying at 130°C) . When submerged in water for 2-3 days at 19 – 21°C, these cracks start at the north pole and at the south pole in the groove and to the other side, while the white material swells. This could be secured by microscopic imaging (cracking pole-to-pole short distance after about 2 - 3 h of air-drying). The north pole is not glossy and Fig. 1a depicts a frontal view with such beginning crack to the right of an otherwise complete macadamia seed. The side-view of a cracked wooden shell fragment through the north pole (from a different sample) in Fig. 1b indicates a channel that bents and becomes narrower while extending down to the adjacent insulating black layer (see below), part of which is seen at the down right corner. Images at lower magnification indicate a length of 10 mm with a further bent following the spherical overall shape. It cannot be excluded that the cracking created part of the extended channel, but such channels must be used for the necessary soaking of water for assisting germination by initial cracks from pole to displaced pole via the shorter distance. The frontal ring illumination is particularly versatile for imaging of these details by avoiding disturbing shadows.

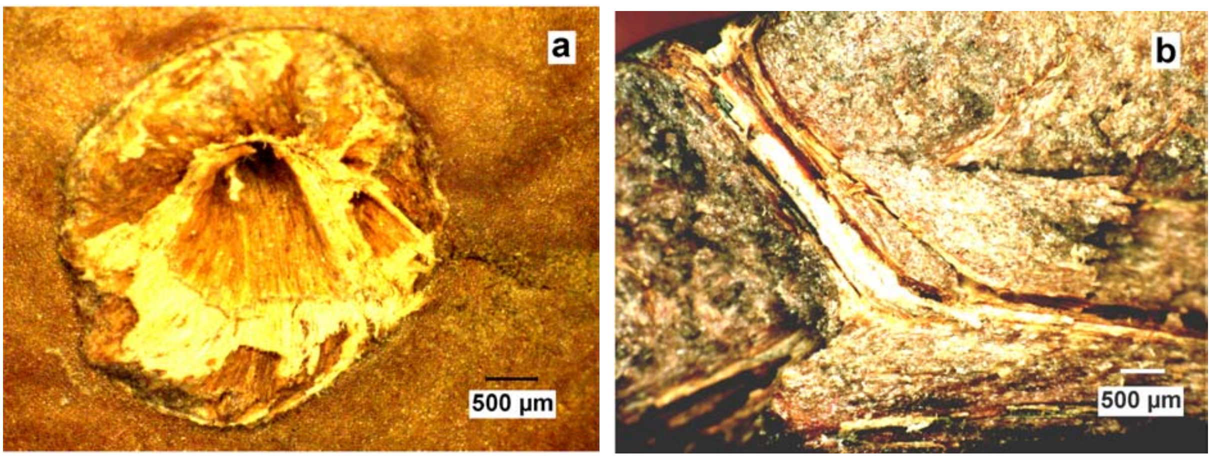

Fig. 1. Micrograph of the north pole region of a macadamia wooden shell at frontal ring illumination; a) facing with a beginning crack; some of the fibrous material had been removed with a needle; b) different sample cracked through the north pole showing the channel extending down and continuing further down; part of the black insulating layer is seen at the down right corner of the image.

The irregularly distributed light-brown regions seem to be further starting points for cracks upon external pressure by a vice. This derives from consistent alignment of divided light-brown spots at the borders of the fragments and by incomplete cracks starting from the light-brown zones in larger fragments both upon application of polar or equatorial pressure. Images are from the overwhelming brown surface of de-waxed seeds if not stated otherwise. The largest part of the wooden shells of cracked macadamia shells is different from the outer hardshell and consists of softer wood that can be easily chewed. The softwood is 5 mm wide at the north pole (Fig.1b) and shrinks to 1.5 mm in the equatorial and southern parts. It is tightly connected to an insulating black (north hemisphere) and an insulating white (south hemisphere) glossy layer with sharp borderline between them that cannot be removed with a knife without some abrasion of the softer wood material. Residues of the tightly connected kernel material can be removed with a finger-nail without hurting the glossy layers.

Sidewise illumination of the hardshell

The Zeiss microscope allowed for visualizations of the opaque surfaces up to total optical magnifications of 100x. But it distinctly reveals the fullerene-like structure of the surface (Fig. 2). There is a sphere and there are the necessary pentagons and hexagons but also some polygons with less and with more corners. On the average this is to be called fullerene-type. The term "fullerene" is no longer restricted to spherical carbon modifications and their derivatives (for example Li &Li, 2003). A similar texture is seen if sloping spheroid regions are aligned for frontal illumination with the VH-Z500 zoom lens exhibiting large focal range in Fig. 4 below. The walled pentagons and hexagons in Fig. 2 exhibit diameters up to 50 µm and so do their neighbours with less or with more corners. This appears to be a most stabilizing architecture for the spheres. The walling of the polygons is an additional stabilizing element that is also used in planar honeycombs.

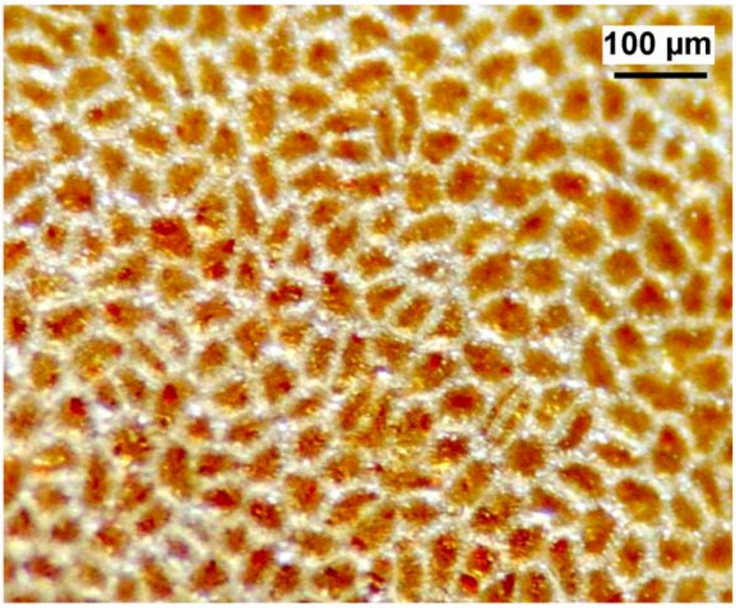

Fig. 2. Micrograph of de-waxed surface of a macadamia hardshell of the equatorial region upon sidewise illumination of a horizontal region showing fullerene-like texture with walled polygons; out of focus borders are mostly removed.

The fullerene-like texture is mechanically very stable. This is evident from the depression site of a triangular vice claw feature from the cracking in the equator region. Fig. 3 shows sharp edges at the depression borders and that the texture is only destroyed at the very end of the triangle where damage occurs. Interestingly, no cracks do start there. This points to high resistance towards deformation against normal load as a consequence of the fullerene-like texture on the sphere. A more detailed analysis is expected at higher enlargement with frontal illumination and the colour spots are additional features.

Fig. 3. Micrograph at sidewise illumination of a macadamia hardshell surface in the horizontally aligned equatorial region at the site where a triangular hard steel structure of the vice claw depressed the surface indicating retention of the surface texture and destruction only at the sharp end of the impression. The red features are different from the circular construction details that can only be seen in Figs. 5 and (partly) 6.

Frontal illumination of the outer macadamia hardshell

The frontal illumination at higher enlargement provides different images if taken in sloping regions when compared to horizontal alignment. The former requires composition of images over larger ranges of focus; the latter is the result of one or two images. Clearly, the sloping case must produce shadows of polygons at one side of the wall edges that can be enhanced by asymmetric frontal illumination. Fig. 4 from a strongly sloping region is the result of 14 composed images at focal point differences of 10 µm that means, a height range of 130 µm on the spheroid surface is covered and flattened to an overall plane. The shadow is to the left side of all features and the fullerene-like texture with walled polygons becomes clearly visible as in Figs. 2 and 3 where a horizontally aligned region was illuminated from a side. The walls around the polygons are stabilising, however, finer details are also hidden under these conditions.

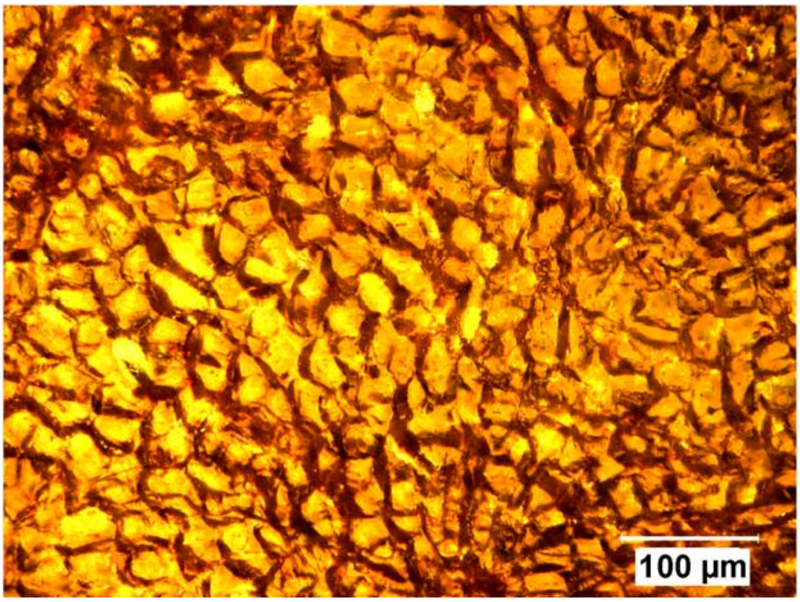

Fig. 4. Micrograph of a macadamia hardshell surface in a sloping close to polar region upon composing 14 images at 10 µm focal distance with asymmetric frontal illumination (bijective) for highest contrast, showing the fullerene-like texture with left-side shadows.

Spheroid surfaces are, of coarse best imaged in horizontal regions with surjective illumination (Fig. 5). An important further structural feature emerges there: frequent small dark circular sites (that must be columnar) mostly outside of the polygons with their walls. This is the new advanced fullerene-type construction that is suggestive for biomimetic engineering. Interestingly, that feature makes drops of water not wetting the seed (even after treatment with detergent) while it does not prevent wetting of the seed when it submerges into water.

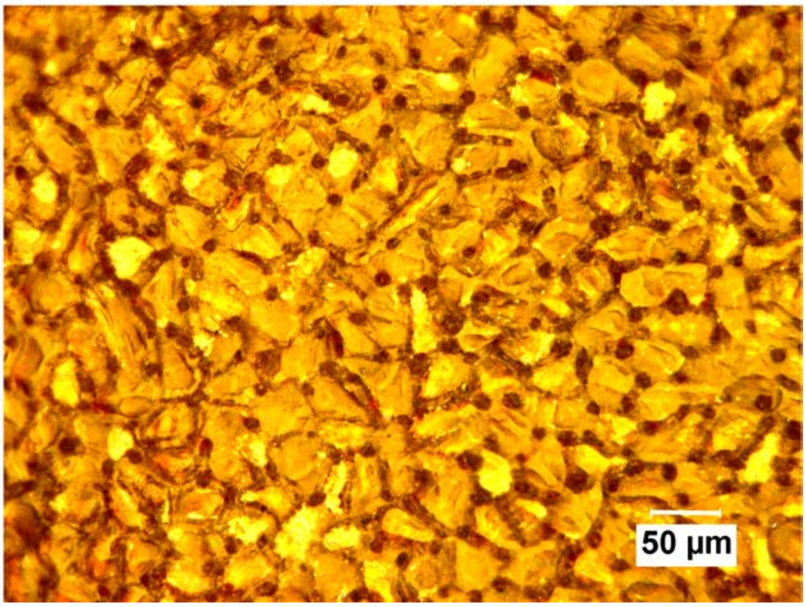

Fig. 5. Micrograph of a macadamia hardshell surface in a horizontally aligned region with surjective illumination (frontal symmetric), showing the fullerene-like texture and additionally dark small circular sites mostly outside of the walled polygons in addition to some red areas.

The function of the circular sites becomes evident when the different texture in the lighter-brown regions is compared. The polygons there are less pronounced and the number of the small dark sites is highly decreased there (almost vanishing) as shown in Fig. 6, which has been taken at a borderline. These differences in texture are best seen upon frontal bijective illumination of horizontally aligned regions. The five small dark features that are in line close to the edge in the right part are not typical for the light-brown zones that are almost free of them. Conversely, the brown zone starts with many larger dark sites from the edge. When the start of mechanically induced cracks from the light-brown regions is recalled this indicates that the dark apparently columnar sites in Fig. 5 (and to the left in Fig. 6) act as less compliant stiffeners increasing the stability of the seed shells against cracking by external pressure. Fiber bundles that are normal to the spheroidal surface achieve the increased toughness.

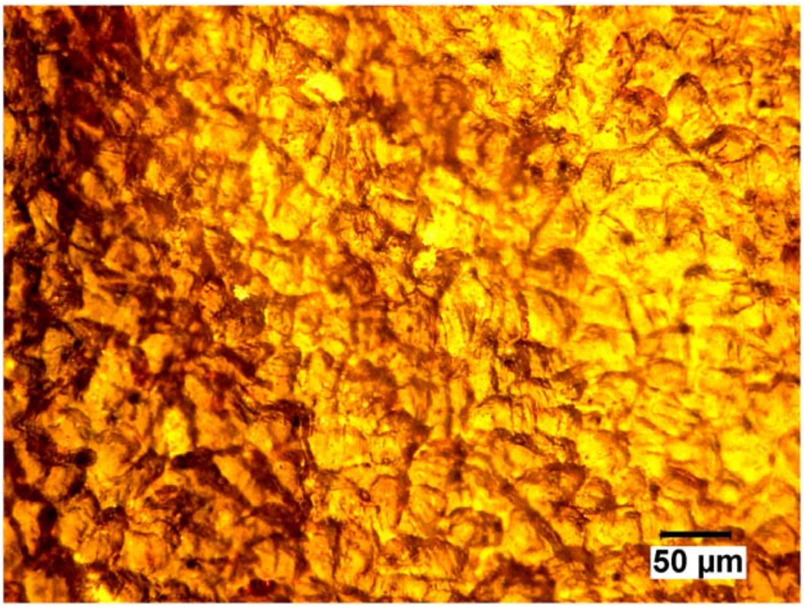

Fig. 6. Micrograph of a macadamia hardshell surface in a horizontally aligned region with bijective illumination at a borderline of the brown bulk and the lighter-brown sections, showing the colour differences, the decreased wall height and the low number of smaller dark stiffeners in the zone to the right.

Depth of the macadamia hardshell

The total depth of the wooden shell varies from 1.5 mm in the equatorial and southern regions to a maximum of 5 mm at the north pole (Fig. 1b). However, there are a very hard outer zone and a softer (chewable) inner zone. Therefore it is of highest interest to distinguish these two by the advanced capabilities of optical microscopy. We pursued several approaches by imaging cut edges of fragments or fissures.

The capabilities of the 3D light microscopy with reconstruction of opaque surfaces are impressively shown by the edge image of a broken macadamia seed shell in Fig. 7. It is seen that the almost vertically aligned outer part is fully structured at a height difference of about 0.5 mm in this sample. The nearly horizontally aligned plane of the softwood indicates a minor step after about 100 -130 µm from the right edge, but this value is not very precise at this enlargement and must be higher resolved.

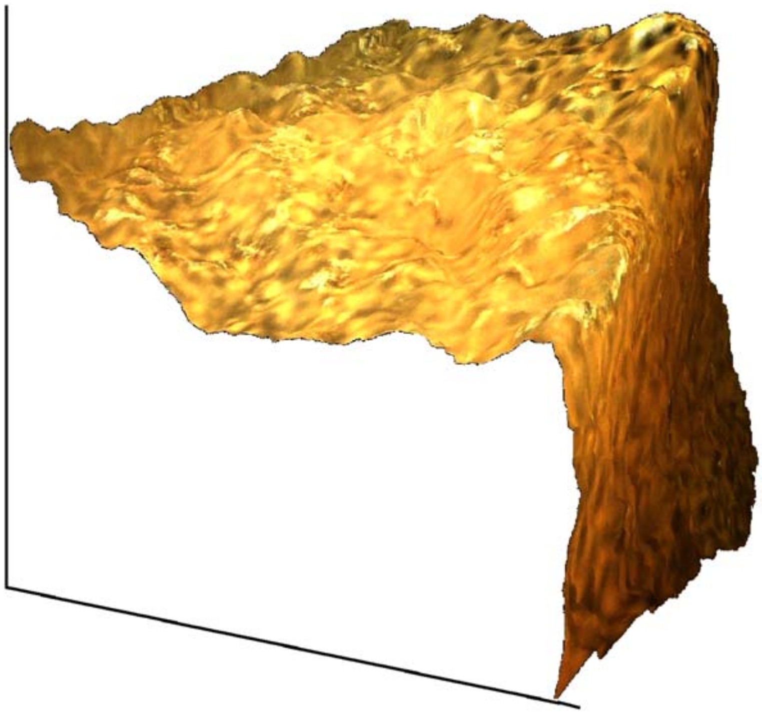

Fig. 7. Microscopic surface reconstruction of the outer edge of a broken macadamia seed shell by composing 12 images at 50 µm focal distance (550 µm) with asymmetric frontal ring illumination; the width line covers 580µm.

A frontal view to the broken edge exhibits a more pronounced step image. Fig. 8 shows the frontal illumination image on the properly aligned broken macadamia outer shell. It exhibits a very clear step in the wooden material. The width of the outer hard shell is thus measured at 160 µm and this appears to be a good estimate, as the heterogeneous composition under it appears less uniform with clusters and larger scale colour differences. The majority of the bundles of fibres in the hardshell are aligned parallel to the outer surface. Only few are normal to it. These are important features of the hardshell architecture: they tell that the polygons in Fig. 5 have the densely packed bundles of fibres in flat orientation, whereas the dark columnar stiffeners must have them vertical. The mechanics of this advanced fullerene structure is thus intuitively understandable. It means that external pressure due to the stiffeners has a harder job for crashing the hardshell than has internal pressure (after soaking water and swelling) that cracks the seed for germination by expansion. Another feature of concern are the red and green spots in Fig. 8. Their nature and function require further studies (also Figs. 2 and 3, that might indicate that the green material can also be generated by mechanical pressure).

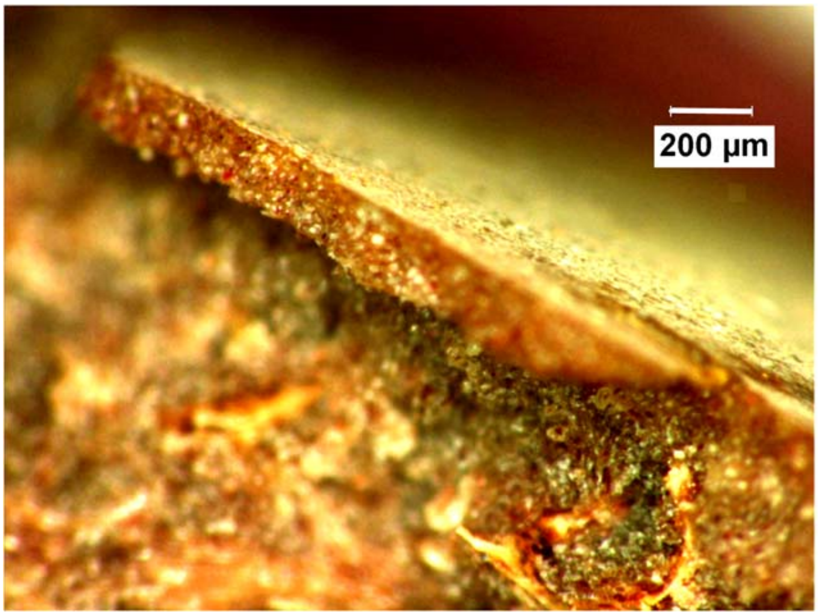

Fig. 8. Frontal micrograph of a broken macadamia seed shell surface's outer edge in the north polar region at frontal illumination indicating a thickness of 160 µm for the outer hardshell and distinct local colour differences at isolated locations; the softer wood material is at lower level.

The delineation of the hardshell width rests on the large difference to the softer (chewable) inner material of the wooden macadamia shell. The softwood is more flexible and it is therefore also possible to judge and secure the width of the hardshell from fissures that did not separate into fragments. Figs. 9a, b exhibit a narrow fissure with average depth of 160 µm. It has uniform slopes and does not seem to enter the softwood. The broader fissure in Fig. 9c seems to additionally penetrate down into softwood as it exhibits extra craters. The overall height of the image is 210 µm and this also secures the 160 µm value for the hardshell. It is highly remarkable that a wooden shell (total density: 1.27 g cm^{-3}) (Jennings & MacMillan, 1986) with a hardshell part of only 160 µm depth of a seed with 2.5 cm diameter requires a force of about 2000 N for being cracked (Lucas et al., 1994; Wang et al., 1994/1995; Jennings & MacMillan, 1986). It should be noted that also very narrow fissures were microscopically found in the light-brown regions. These had a measured depth of about 20 µm and might point to a super hard outer shell zone there, but the 160 µm values are judged to be the ones responsible for the actual cracking, which does not only produce the fully separating cracks. Such marked inhomogeneities of the wooden macadamia seed shell were not reported in the previous SEM studies based on polished cross-sections in the absence of the new 3D-capabilities of digital optical microscopy, when unsuitably isotropic wooden macadamia shells were assumed (no distinction between hard and soft parts) for the theoretical deductions and the data treatment.

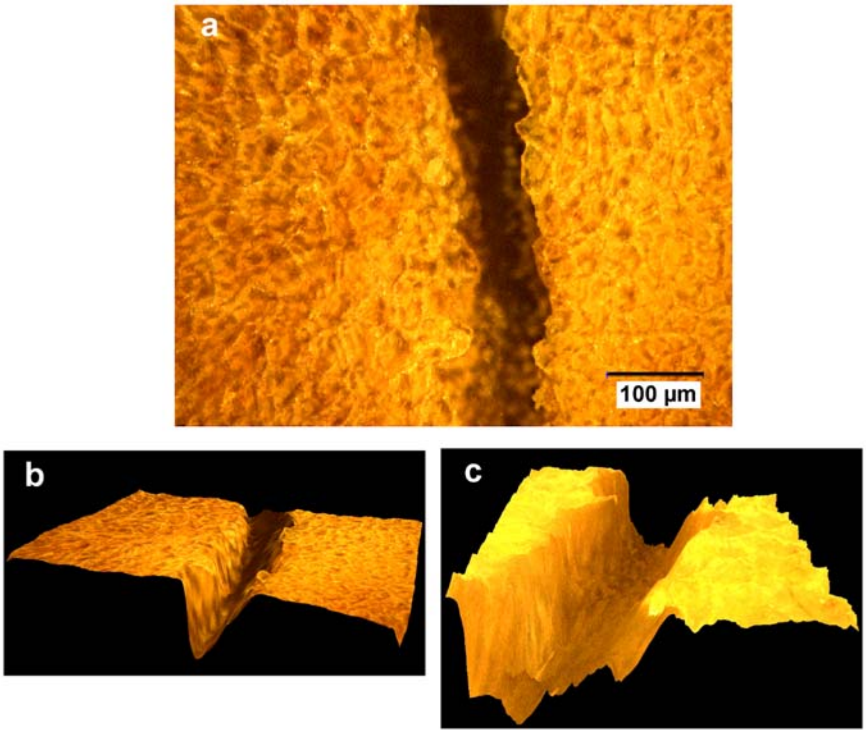

Fig. 9. Microscopic surface reconstruction of fissures in macadamia hardshells; a, b: sloping site with narrow fissure exhibiting sharp bottom at an average depth of 160 µm; c: wider fissure at twice the enlargement with craters entering the soft material; both surface reconstructions composed 22 images each at 10 µm focal distance,

The softer wooden material of the macadamia seed shell

The detailed microscopic inspection of the macadamia wooden shell revealed as yet unreported small red (Figs. 2, 3, 8) and more rarely green spots (Figs. 3, 8) next to the brown and lighter brown zones. The latter consist of lignin (brown), cellulose (colourless), and pentosans (colourless), but their safe differentiation would require nanoscopic resolution. The chemical composition of various seed shells has been described and qualitatively related to their hardness (Hilpert & Krüger, 1939), but without taking into account inhomogeneities and architectural issues. Also the micro-spectrographic and micro-radiographic determination of the lignin and cellulose distribution in wood microtomes for details of sizes down to 1 µm has been described (Lange, 1950). More detailed ^{13}C CPMAS NMR studies revealed the similarity of various seed shell materials with western hemlock wood (a softwood) and hardwood. The related Macadamia integrifolia seed exhibited a ratio of carbohydrate/lignin monomer units of 1.4 and a comparatively high ratio of guaiacyl lignin and syringyl lignin (Preston & Sayer, 1992). It is to be assumed that the Macadamia ternifolia wooden shell has a very similar chemical composition. However, the nature and function of the now easily detected red and green spots in the Macadamia ternifolia hardshell is unclear. Interestingly, these spots occur in the hardshell, in the softer wooden zone, and the black glossy layer also exhibits red spots that cluster there. Nothing of that was reported for micrographs of polished cross-sections after heat treatment for three weeks up to 333 K (Jennings & MacMillan, 1986). The intensely coloured spots are spread over the freshly broken surfaces. For a more detailed investigation of the softwood zones we look at the rough cracked surfaces both normal and parallel to the hardshell with surface reconstructions at varying enlargements below.

Freshly cracked soft wooden surfaces normal to the macadamia hardshell

Bundles of fibres at the cracked surface are observed in the softer wooden part of the macadamia seed shell if it is broken normal to the outer hardshell (Fig. 10). The texture is very complicated and diverse at this low magnification. Most fibres end here that means they are parallel to the surface as so also in the hardshell. But some lie flat (probably in direction of the stiffeners on the surface) and there occur certain domains. It is imaginable that such structure will swell when water is soaked in via north pole channel for building the internal pressure for pole-to-pole cracking.

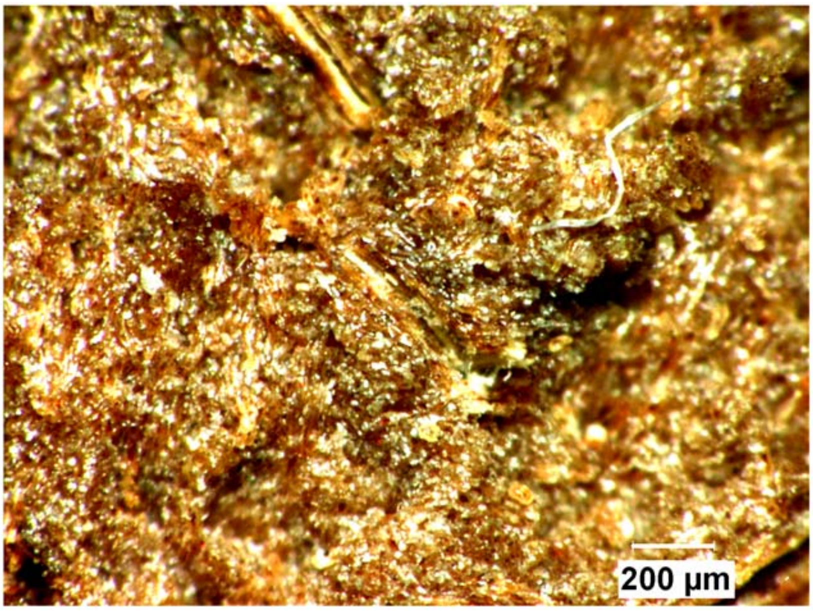

Fig. 10. Micrograph of a fresh broken surface in the soft wooden region normal to the macadamia outer hardshell, showing most bundles of fibres ending here and the occurrence of domains.

At larger magnifications and surface reconstruction it is possible to resolve the ends of the disrupted fibre bundles at a very uniform site (Fig.11). It appears, that this region consisted exclusively of fibres aligned in one direction. These are torn off bundles of fibres at similar length that never reached the hardshell. Interestingly, the valleys between the steep peaks cross at right angles and the counterpart from the breakage should correspond to the image of Fig. 11.

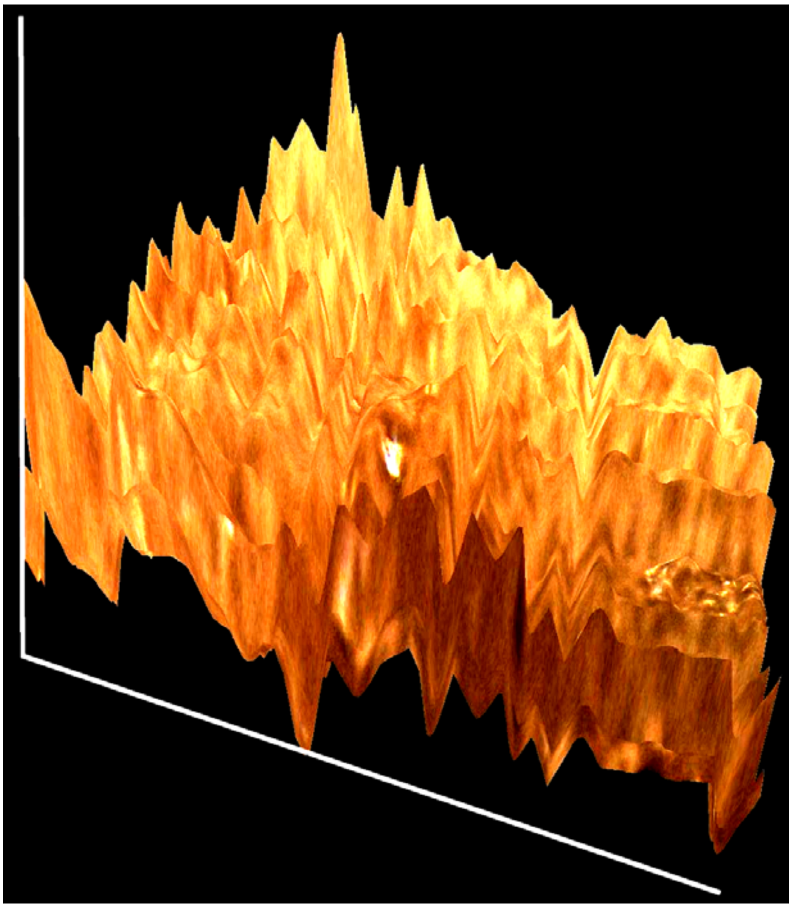

Fig. 11. Microscopic surface reconstruction at a uniform site of the soft wooden region normal to the macadamia outer hardshell by composing 6 images at a focal distance of 5 µm; the width line covers 150 µm

At even higher magnification in another region (Fig. 12) it is clearly seen, that the peaks represent bundles of fibres. Despite the colour change by strong contrast settings green spots and red regions can be differentiated.

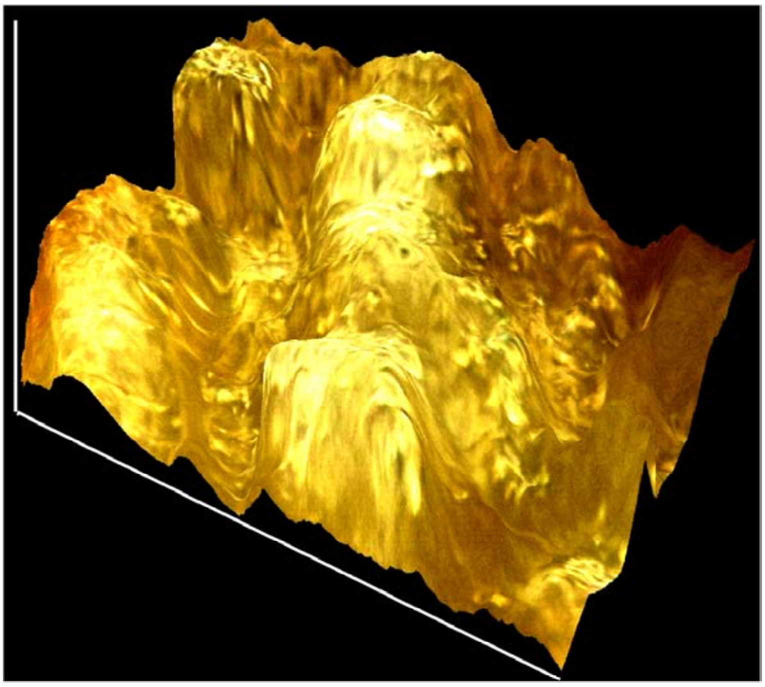

Fig. 12. Microscopic surface reconstruction of a freshly broken surface in the soft wooden region normal to the macadamia outer hardshell, composing 10 images at a focal distance of 2 µm; flat and steep hills out of fibre bundles are seen; the width line covers 76 µm.

Freshly cracked surfaces roughly parallel to the macadamia hardshell

If the macadamia seed is cracked by pressure to the equatorial region it is also possible to collect fragments of the softer wooden part of the shell that are tangentially broken with respect to the outer shell. This provides now the fibres that were torn off in Figs. 10 - 12 as flat lying bundles of fibres as is evidenced in Fig. 13. It is also seen that some end vertically and thus are torn off. The cluster formation of Fig. 10 is also verified in Fig.13. Therefore it appears that the orientation of the brakeage is not at random but that weaker borders at the interfaces care for preferred breakage in the softwood part. The frequency of the red spots is enhanced when compared to the normal cuts and some green spots are also seen.

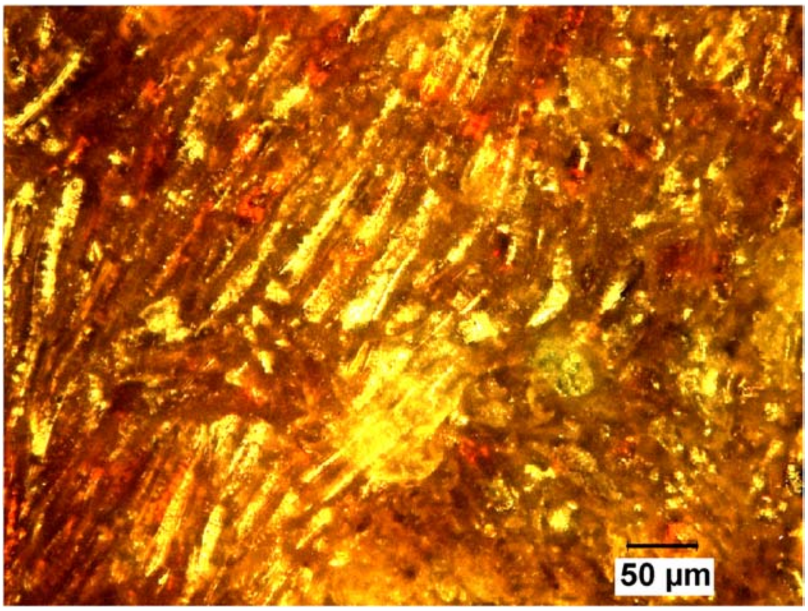

Fig. 13. Micrograph of a fresh broken surface in the soft wooden region roughly parallel, to the macadamia outer hardshell, composing 8 images at 20 µm focal distance with bijective frontal illumination.

The shapes of the red spots and of the bundles are imaged at 8-fold higher optical enlargement with surface reconstruction in Fig. 14. It is clearly seen that the red colouration has sharp borders and is embedded in the fibrous structure that consists of various materials that glue the cellulose fibres together. Conversely, the green spots appear at separate structures as is shown in Fig. 15 at an area with both flat and vertical bundles of fibres.

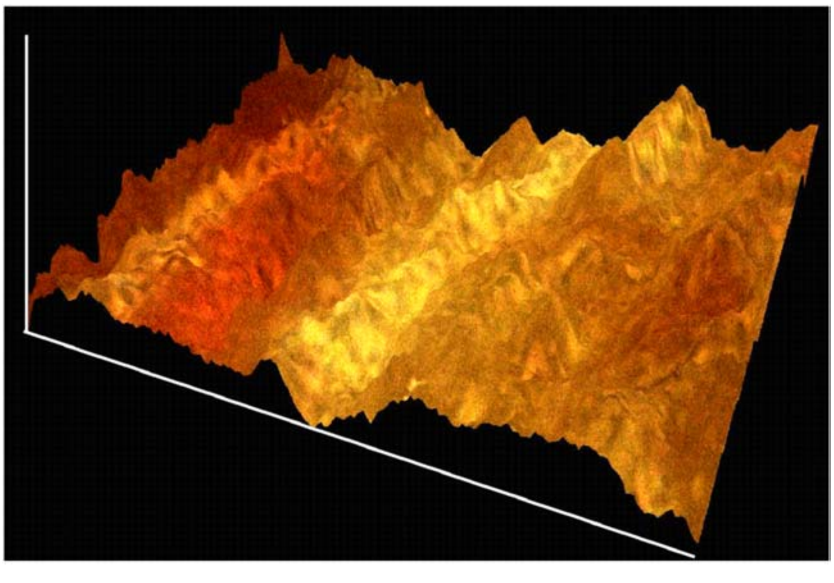

Fig. 14. Microscopic reconstruction of a freshly broken surface in the soft wooden region roughly parallel to the macadamia outer hardshell, composing 6 images at 5 µm focal distance taken with asymmetric frontal illumination; the width line covers 76 µm.

A very rough surface region is reconstructed in Fig. 15. Parallel flat fibre bundles are located between high torn off vertical bundles in a freshly broken surface of the softer wood that occurred roughly parallel to the outer surface of the seed. Most spectacular is the green fibrous grain amidst the more abundant fibrous features. While the comparatively rare green spots on the outer shell of Fig. 3 might be challenged as some destructive chemical change on the surface, the large distinct green feature in Fig. 15 with very sharp borders secures the inherent presence of the green spots. The very sharp borders and the occurrence within the previously complete (prior to the cracking) de-waxed seed excludes influences of the mechanical cracking, or by some microorganisms or by any spoiling from some action of external chemical reagents such as complexing metal ions or dyes and the like. The shape of the green block either coloured or as a dye pigment suggests a cluster that is different from the fibres. Further dark green clusters are recognized in Figs. 8 and 10. It might be chlorophyll or some other organometallic complex as a building block with some as yet unknown functionality. Micro-tomographic techniques should be suitable for clarifying these points.

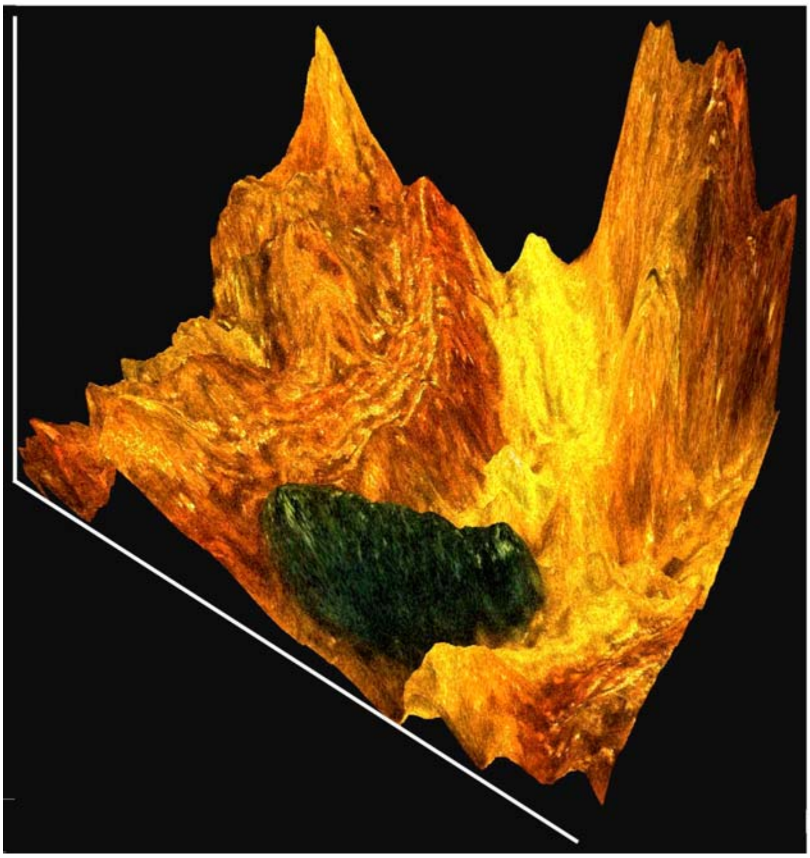

Fig. 15. Microscopic reconstruction of a freshly broken surface in the softer wooden region at a very rough site roughly parallel to the macadamia hardshell, composing 11 images at 20 µm focal distance with bijective frontal illumination, the width line covers 580 µm.

Discussion

The macadamia hardshell (160 µm thick part of the wooden shell) owes its extreme resistance against external cracking to its advanced fullerene-like construction of more compliant larger polygons with additional small columnar vertical stiffeners. The polygons are about 50 µm wide, exhibit edge walls and consist of flat lying fibres according to the microstructure of the fractured hardshell in Fig. 8 with overwhelming ends of bundles there. The columnar stiffeners are likely candidates for the bundles of fibres that end normal on the spheroid surface of the hardshell. This architecture is the reason for the extreme cracking toughness of the 160 µm thick shell. If the stiffeners are missing as in the lighter-brown regions of the surface (Fig. 6), the crack resistance is decreased as only the walls around the polygons decrease the compliance. Cracks start from there and from the poles upon external pressure. The totally different cracking upon internal pressure after the necessary soaking of water through the imaged north pole channel structure (Fig. 1) for the germination is also comprehended: the distance between the polygons is widened upon internal pressure and cracking can occur easier than by compression from the outside.
The new bionic construction feature could only be revealed by using digital optical microscopy with unlimited depth of focus, frontal illumination, and three-dimensional surface reconstruction. This proved very helpful and versatile for the understanding of the extraordinary toughness of macadamia seeds against cracking. Additionally it reveals hitherto unreported colour centres, the function of which deserves further botanical research. The new 3D imaging of very rough oblique surfaces from the mm to the submicron ranges with differentiation of local colour spots are highly diagnostic and provide new insights. The applied composition technique of various images at different point of focus is connected with some flattening of the images, but structural details are clearly extracted from the images. For example, a spheroid surface appears as a projection to a plane in the presence of random features (e.g. Fig. 4, also upon 3D surface reconstruction), but the width of composed focal distance and the radius of the sphere give the height of the imaged sphere segment. Furthermore, grooves (Fig. 9) and cylinders (Fig. 14) keep their shapes, rectangular edges (Fig. 7) keep the right angle between the adjacent planes, and the heights in images such as Figs. 11, 12, 15 are pretty close to reality. The images with frontal illumination do not throw shadows in flat regions (Fig. 5) unlike sloping regions (Fig. 4), but a means of contrast improvement is the feature of asymmetric frontal (bijective) ring illumination creating shadow by light attenuation from one side. The flattening of a spherical surface to a plane must not be disadvantageous. It helps in extracting the basic texture if a horizontal site cannot be aligned, or if a sphere is too small. Even textures at very steep surfaces are recognized by the electronic composition of various images at different focus.
It should be noted here that not all hardshells of seeds use the fullerene or the advanced fullerene motif for their construction. For example, the wooden shells of the more extended pecan seeds or coconuts do not profit from such texture, as can be easily shown by optical 3D microscopy with full focal depth capability and surface reconstruction. The same is true for hen’s eggs, to mention another example of interest here, but the pigeon egg (of Columba palumbus) exhibits a fullerene-type texture.

The advanced light microscopic inspection of the macadamia wooden shell surface microstructure, pole channel, cracked surfaces and developments of cracks revealed a large number of new facts, which are of importance for bionics and botany. It does not rely on microtomes or polished and metallised cross-sections but avoids altering the original structures. It is to be expected that the advanced fullerene-like texture will also be found as the construction principle of further hardshells and that the additional stiffeners can considerably improve the stability of such architectures with compliant materials also at much larger scales. For example, the geodesic domes of W. Bauersfeld (construction of the Carl Zeiss Planetarium Jena in 1922) and Buckminster Fuller (US Pats. 2682235, 1954 and 2914074, 1959 and others) consisting of all-triangle elements or even better the Yacoe-Davis geotangent domes (US Pat. 4825602; 1989) consisting of pentagons and hexagons (on the molecular scale closed Yacoe-Davis spheres are now generally called "Fullerenes" or "buckyballs") have close similarity to the macadamia hardshell surface, but they miss the enforcement of the normal stiffeners. The same is true for monolithic concrete domes of Dome Technology Inc. (Idaho Falls, USA, since 1979), that use framed mats of steel rebar tangentially aligned to the spheroid surface but not any normal stiffeners (http://www.dometech.com/process/construction.html).
The enormous stability of the 160 µm hardshell of macadamia seeds that withstand forces of up to 2000 N is highly suggesting for using its construction principle.

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