Photoelastic Stress Response of Complex 3D-Printed Particle Shapes

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Abstract

Stress visualization within 3-dimensional particles undergoing dynamic processes can greatly advance our understanding of complex particle behaviors. Traditional photoelastic stress visualization methods suffer inherent limitations from lack of available technology for complex particle production. Recently, 3D-printing has created new possibilities for enhancing the scope of stress analysis within physically representative granules. Here, we investigate opportunities offered by 3D-printing a granular material with photoelastic properties. We report the results of X-ray computed tomography and 3D-printing, combined with traditional photoelastic analysis, to visualize strain exhibited within simple discs to reproduced coffee beans. We find that the choice of print layer orientation with respect to the force load affects the optical properties of the discs, without a significant difference in their mechanical properties. Furthermore, we present a first, semi-quantified, measurement of stresses within 3D-printed particles of complex shape. The promising data shows potential for applying this method to complex assemblies of 3-dimensional particles.

Topical Area: Particle Technology and Fluidization
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1 Introduction

Photoelastic methods have been widely used to experimentally identify regions of stress within single and bulk 2D particle systems[1]. A visualization is shown in Figure 1 with the stress apparent on the disc as an alternating bright/dark fringe pattern. The earliest report of this method was in the late 1930s where it was applied to powdered glass for the application to a Christensen filter [2]. In the 1950s, a report by Wakabayashi applied photoelastic methods to determine stress in a powder mass [3]. Researchers have since drawn on the technique to further their understanding of complex systems, in particular through the investigation of localized force transmission commonly known as “force chains” [4 5]. The bulk behaviors of real-world materials, such as solids, foods and industrial products are thought to exhibit similar internal patterns of stress.

Figure 1. Image illustrating the photoelastic response of a disc subject to diametric load under darkfield configuration with the isochromatic fringes numbered [6].

To date, quantitative studies are limited to 2D aspects of particle systems, and have focused on flat spherical shapes i.e. discs [7], with fewer reports on flat non-spherical shapes i.e. pentagons [8]. In response to these experimental limitations, there have been advancements in computational modelling using Finite Element Analysis (FEA). This method is capable of analyzing complex particle systems in a relatively short timeframe and potentially eliminate the need for material resources [9]. FEA is suited to model and predict the photoelastic behavior of individual complex particle shapes [10].

The underlying photoelastic mechanism in this technique is the double refraction of the polarized light incident on transparent polymer, which is sensitive to the local stress along the optical path [11]. The phase difference between the two paths is visually apparent as isochromatic stress fringes [1]. Various experimental configurations (brightfield, darkfield, reflection, transmission) show such stress visualizations [1 6 12]. The simplest example is the photoelastic response for diametric loading on disc shaped particles, which has been well established analytically [1]. For this shape, the number of observed bright and dark fringes increases with the force applied to the particle and can be used as a means of calibration for quantitative analysis (Supplementary video 1). The intensity I (x,y) at a particular point on the disc can be calculated by using equation 1 [13], given by the principal stress difference at that point, (σ_1- σ_2). Under monochromatic illumination, F_σ = λ/Ch, the thickness is given by (h) and the stress optic coefficient (C) is a material constant. It is important to note that when a disc is subjected to 2D stress, the fringe order is proportional to the thickness [1].

$$I(x,y)=I_o\sin^2\frac{\pi(\sigma_1-\sigma_2)}{F_\sigma} \tag{1}$$

The gradient-squared (G^2) method [14] is a semi-quantitative measurement method for quantifying the 2D stress on a particle with an arbitrary number of vector contact forces, developed by Behringer *et al.* The quantity is calculated by taking the local (pixel-wise) gradient, squaring, and averaging over all pixels in a particle or system, according to the equation:

$$G^2=\sum_{i,j}\left[\left(I_{i+1\,j}-I_{i-1\,j}\right)^2+\left(I_{ij+1}-I_{ij-1}\right)^2+\frac{1}{2}\left(I_{i+1\,j+1}-I_{i-1\,j-1}\right)^2+\frac{1}{2}\left(I_{i+1\,j-1}-I_{i-1\,j+1}\right)^2\right] \tag{2}$$

Because of its simplicity and ease of calculation, it has been widely used for quantifying stresses in granular systems [15]. Since this method takes into account the image of a particle, it can be applied to particles of any number, shape or combination of both, including non-circular particles [16].

Until recently, most studies used flat particles because these (1) provide the simplest interpretation of the optical patterns and (2) can be machined from flat sheets or cast in molds. The recent introduction of sophisticated 3D-printing has changed this. Wang *et al.* led a comprehensive characterization of the commercial 3D-printing material VeroClear, which has photoelastic properties, and is used in standard Stratasys Connex Objet printers [17]. Wang *et al.* 3D printed rock samples using VeroClear material. The internal structure and mechanical response of rock masses vary widely due to the sedimentary and forming process of natural reservoir rocks [18]. Thus it becomes challenging to develop a transparent photoelastic material which closely matches the material mechanical properties of the 3D-printed copy of the real rock sample under analysis. They reported that under triaxial conditions, the samples with horizontal layers (S-Z) have a higher stiffness compared with the vertical layers (S-X and S-Y). However, little variance was found in compression strength under different confining pressures.

Recent studies have reported the utilization of 3D-printing with photoelastic materials to investigate the stress visualization of systems found in the real world. X-ray tomography may be used to obtain the internal and external shape of systems such as geological rocks, coal, or soil, for the purpose of converting to 3D-printable files, and their subsequent stress analysis has been reported [19-21]. For example, Ju *et al.* investigated 3D-printed rock that contains inherent internal fractures for frozen stress and photoelastic tests. It was reported that the mechanical properties of the rock (Poisson’s ratio, elastic modulus) were close to that of the 3D-printed rock [19]. The stress visualization was modelled by means of FEA. In contrast, Mathews *et al.* reported an inconsistency between the 3D-printing material and the original material as the rock is denser and contains a higher atomic number [20].

3D-printing has the potential to be used not only to replicate real particle shapes naturally formed in the environment, but also for understanding the stress behavior of these complex particle systems. The behavior of these particle shapes from the real world, which have intricate external and internal geometries, has not yet been investigated using 3D-printing. This proposed advancement may bring researchers one step closer to deriving the algorithms necessary for stress visualization and quantification involving complex particle shapes. The slightest change in dimensions of the shape could have a significant impact on the photoelastic response. Therefore, the combination of 3D-printing complex photoelastic particles, and use of Finite Element Methods to model such data, could lead to the development of enhanced models for 3-dimensional stress analysis of complex particle systems [22].

In this study, we report the optical and mechanical properties of 3D-printed discs with different alignments of the print layer. A control disc produced by traditional manufacturing methods was used as a comparative benchmark. Calibration of the discs showed little difference in mechanical properties of the 3D printing materials with different alignments of the print layer. As a proof-of-concept, we quantitatively investigate the photoelastic response of a naturally-occurring complex particle -- a 3D coffee bean – including internal and external surfaces with positive and negative curvature. We find that the presence of internal voids complicates stress visualization, and therefore performed additional qualitative and quantitative tests on a modified bean that contained no voids. Furthermore, we extracted a lateral slice of the bean containing the voids and digitally extruded the cross-section to observe the photoelastic response 3D shape in a 2D perspective. We found good visual agreement of the principal stress distribution between FEA and experiment, which is promising for the future development of the approach.

2 Material and Methods

2.1 Particle shape construction

The cylindrical disc shape (diameter 20 mm, thickness 10 mm) was created using Autodesk Inventor CAD software and exported as an *.STL file for 3D-printing. To reproduce the complex external and internal shape of a coffee bean, X-ray Computed Tomography (Zeiss Xradia 520 Versa XCT) was used to create a 3D scan of a real decaffeinated coffee bean. This technique records projection images of the x-ray energy transmitted at each one of 360° angles oriented with respect to the sample. The voltage and current required by the x-ray beam [20] is dependent on the sample thickness and material type; for this study, the optimum contrast of the coffee bean required 40 kV and 74 mA.

Materialise MIMICS software was used to reconstruct the XCT output DICOM images into a closed surface mesh *.STL file ready for 3D-printing [23]. The original size of the reconstructed coffee bean (11 x 4 x 7 mm) was doubled, and the rounded ends truncated to assist with handling and applying loads during compression testing. Three versions of this coffee bean geometry were investigated; one containing its internal void structure, another simplified version with internal voids removed, and a 2D extruded cross-section.

2.2 Particle materials

The 3D-printed particles were made using Stratasys VeroClear UV-curable polymer, an acrylate-based photopolymer with photoelastic properties. For this study, the mechanical properties were experimentally measured using the ASTM D638 standard tensile and ASTM D695 standard compression tests and the data summarized in Table 1. The tensile specimen of Type-I design for the yield and tensile strengths and the standard compression cylinder specimen design for the elastic modulus were used [24 25]. We investigated three orientations for the build of the tensile specimen and two orientations for the compression specimen on the 3D printer. Figure 2 shows the position of each specimen on the platform so that the print layers are parallel (Fig. 2A and 2D) or perpendicular (Fig. 2B, 2C and 2E) to the platform when they are when in the upright orientation. These tests were to determine whether the material mechanical properties are dependent on the orientation of the print layers.

Figure 2. Schematic illustrating the arrangement of the print layers for each specimen tested. (A) Tensile specimen - S1 (B) Tensile specimen - S2 (C) Tensile specimen - S3 (D) Compression specimen – S4 and (E) Compression specimen - S5.

2.3 3D-printing of particles

A Stratasys Objet500 Connex3 3D printer was used to additively manufacture the VeroClear particles using polymer jetting. This process involves selective jetting and polymerization of a photo-polymer resin to build up layers of a 3-dimensional object. Compatible water-soluble material is used to support overhanging regions and internal voids, and is removed in post-manufacture processing. It is important to note that support material fully encapsulated within the part could not be removed. Input geometry *.STL files were prepared for printing using Objet Studio slicing software to set build parameters and generate support structures. High quality 16µm layers at an XY-resolution of 600 DPI were specified.

The discs were 3D-printed in the same manner as the ASTM compression standard specimens to determine whether the orientation of the print layers affects the optical properties of the particle. One disc typically takes 33 min to print in high-quality mode and requires six grams of material and two grams of support material. When multiple discs are printed simultaneously the machine requires less time, for example 44 discs require two hours to print. Similarly, one coffee bean requires four grams of material and two grams of support and takes 35 minutes to print while 40 beans will require one hour to print. An Olympus SZ61 DP22 macroscope was used to capture images of the resulting particles.

2.4 Laser cutting of disc particles

The control particles were laser cut from 10mm sheets of PMMA (polymethyl methacrylate) using a Trotec Speedy 500 laser cutter with 120-watt CO_2 laser. Adobe Illustrator was used to create the 2D profiles then exported as .DXF files for input to the laser cutter.

2.5 Instron compression of particles using the circularly polarized light configuration

The brightfield configuration used consists of circularly polarizing filters (CIR-PL), with the same chirality on either side of the sample (Fig. 3). CIR-PL filters consist of a quarter-wave plate on one side and a linear polarizer on the other side. The quarter-wave plates were placed on the sides closest to the sample. An opaque acrylic sheet was placed between the monochromatic sodium lamp (wavelength 589 nm) and the first CIR-PL for uniform distribution of the light.

Individual particles were placed between the steel plates on an Instron 5959 electromechanical universal test machine (50kN load cell). A strain rate of 1 mm/min was specified, up to a maximum displacement of 2.0 mm. Three specimens of each type were individually tested, while load and displacement was recorded at a rate of 10 Hz.

The images were recorded with a PCO edge, 4.2 monochrome high-speed camera with rolling shutter. TIFF images of the particle compression were taken at 10 frames per second with a resolution of 2048 x 2048 pixels. A black acrylic cage with two cut-out holes for placement of the filters was placed around the compression plates in order to contain as much of the polarized light in the cage and prevent polarized light from interfering. It was also used as a safety measure to prevent flying shards in the instance of particle compression failure.

Figure 3. Circular polarized light with a brightfield configuration set up around the Instron. A. Monochromatic sodium lamp, B. Light diffuser (acrylic sheet), C. Linear polarizer, D. ¼

wave plate, E. compression plates, F. ¼ wave plate, G. Linear polarizer, H. Camera recorder

2.6 Gradient-squared (G^2) method for semi-quantification of 2D stress on system

MATLAB Image Processing Toolbox was used to segment the Tiff images and isolate the foreground particle from the background. MATLAB was then used to implement the G^2 method on the foreground pixel data representing the intensity of the visible stress fringes. This process involved calculating the mean value of the squared gradient of the discrete light intensity pixel data. The G^2 values were then plotted against the corresponding measured test load which was normalized by the average cross-section area perpendicular to the load direction. The G^2 method was applied to the control disc and all 3D-printed particles in 2D and 3D.

2.7 Finite-Element Analysis of the particle compression

Quasi-static 2D plane stress FEA was conducted on the cylindrical disc and the 2D extruded bean cross-section using ANSYS Mechanical. The VeroClear material was modelled as isotropically linearly elastic with modulus 2500 MPa and Poisson's ratio 0.38. Loads were applied using zero-slip contacts with flat rigid plates, the lower plate being fixed and the upper plate having a ramped 2 mm displacement. Solutions were obtained using the direct MAPDL solver and the Newton-Raphson method due to non-linearities associated with contacts and relatively large deformation.

Results of a mesh convergence study that monitored the reaction force at the displacement boundary conditions indicated a mesh independent solution using uniformly sized second-order quadrilateral elements (maximum nominal size 0.125 mm for the cylinder and 0.25

mm for the bean cross-section). The final finite element meshes selected to balance accuracy and solve time used 0.15 mm and 0.2 mm elements for the cylinder and digitally extruded bean cross-section, respectively. Additional refinement was added around regions where high stress gradients were observed.

The principal stresses were of particular interest from the analysis results. Specifically, the difference in the magnitude of the minimum and maximum principal stress was used to create a user-defined result that implemented the stress-optic equation (equation 1) to visualize the expected stress fringes.

2.8 Ray tracing

The image of the unloaded 3D printed coffee bean was ray-traced in order to determine whether the dark shadows (as shown in Figure 11A) are due to an inherent photoelastic stress or refraction. This method involved passing light through the coffee bean with matching and non-matching refractive index as the VeroClear material. The rotation of polarization due to the waveplate-like behavior of acrylic was not accounted for. Autodesk Maya software was used to construct a virtual representation of the polariscope test environment, using reference images to approximately match lighting, material, and camera setup. The Monte-Carlo based renderer Arnold was then used to render images of test specimens and set refractive index of 1.52 on the initial unloaded appearance of the specimens.

3 Results and Discussion

3.1 Stress visualization of a 3D-printed disc

We first examined cylindrical disc shapes as a means of calibration to understand the optical effects of 3D-printed particles at given orientations. As a comparison to the 3D-printed particles, a control disc was also examined which was laser cut from acrylic sheets. The images of the 3D-printed and laser cut discs before compression in natural light are shown in Figure 4A and 4B, respectively. The translucent 3D-printed disc contains layers while the transparent laser cut disc contains no layers; both materials possess photoelastic properties.

Figure 4. Image of discs (dimensions: thickness 10 mm, diameter 20 mm) procured by two different methods (A) 3D-printed in VeroClear and (B) laser cut from acrylic sheets.

Among the challenges of polymer 3D printing is the inherent anisotropy of 3D-printed particles because of the photo-polymerization which connects each new layer to the next. This could lead to different optical and mechanical properties based on the print layer arrangement and shape of the particle under compression. It is possible that there might be a range of properties for a given 3D-printed particle, since the microstructure of the layers would be different based on the orientation of the particle relative to the imposed compression. Figure 5A and B show the particle positions on the 3D printing build platform. Figure 5C shows a schematic of the particles between the compression plates and the print layer orientations with respect to the compression plates, which are referred to as parallel and perpendicular.

Figure 5. A schematic of the particle orientations and the direction of build on the 3D printer platform showing (A) parallel and (B) perpendicular print layers when the discs are

in the upright position. (C) the Instron setup showing the particle print layer arrangement with respect the compression plates.

The orientation shown in Figure 5A comprises of 1250 layers stacked in the direction of the height of the disc (20mm), whereas Figure 5B contains half the number of layers stacked to make the thickness of the disc (10mm). When the particles are placed between the compression plates, they are viewed through a *brightfield* setup. Note that Figure 6A shows the image of an unloaded particle with parallel print layers, starting off *dark* prior to compression. In contrast, Figure 6B shows the image of an unloaded particle with perpendicular print layers which starts off light, as expected to be observed with a brightfield setup. Acrylic-based polymers (such as VeroClear) act as optical waveplates and rotate the polarization of light, unlike more favorable materials typically chosen for photoelastic materials. This rotation, in concert with the microstructure arising from the two different alignments of the 3D printing process, makes the resulting discs differ in their optical response even when unloaded. Were these particles to be used for quantitative force measurements, it would be necessary to account for this baseline amount of optical rotation through the use of a calibrated waveplate, specific to the chosen print-orientation and particle thickness. Finally, it is important to note that the stripes observed on Figure 6B are not indicative of the print layers but arise from the traversing 3D printing nozzle creating a single layer.

Figure 6. Image of an unloaded disc viewed through the brightfield configuration with print layers (A) parallel and (B) perpendicular to the compression plates.

To simplify the issue of anisotropy, only pre-defined orientations were explored to examine whether there is an effect on the optical properties of 3D-printed discs during compression.

The top row of Figure 6 illustrates the pre-defined orientations with the placement of all discs (3D-printed and control) as they are between the compression plates. Figure 7A, B and C illustrate three configurations investigated for the 3D-printed particle with parallel print layers. Figure 7A shows the disc with the print layers exactly parallel to the compression plates, which is the 0° position. Figure 7B shows the disc rotated 45° anticlockwise so that the print layers are at a 45° angle to the compression plates. Lastly, Figure 7C shows the disc rotated a further 45° anticlockwise so the print layers are at a 90° angle to the compression plates. The 3D-printed disc with print layers perpendicular are shown in Figure 7D. Figure 6E shows the laser cut disc made from acrylic sheets not containing any layers used as the control.

The middle row images in Figure 7 show the very first recorded isochromatic fringe (N=1) observed for each of the discs. The alignment of the fringe with respect to the applied diametric contact force varies for each configuration. The 3D-printed disc with print layers perpendicular to the steel plates (Fig 7D) show a stress fringe more comparable to the control disc (Fig 7E). Fig 7A also shows the first recorded fringe to be similar, however, the outer edge of the disc contains an uncharacteristic silhouette partly due to the further rotation of polarization of light and the print layer microstructure. Furthermore, Fig 7B and 7C show a slightly distorted/skewed first recorded fringes as well as an additional uncharacteristic silhouette on the outer edge. For this reason, the complex particle shape was selected in this study for printing with the layers perpendicular to the steel plates.

The bottom row images in Figure 7 show all discs at 5 fringes (N=5), the fringe cycle appears to be the consistent with what has been reported in literature [6]. Force measurements were taken for N=5 to check whether the shape of the particle has a significant effect on the material properties. For the discs with parallel print layers (Fig. 7A, B and C), the uncharacteristic silhouette on the outer edge of the discs is pushed further to the edge with the addition of more fringes. A summary of the force load (N) and displacement (mm) required to reach N=5 is given in Table 2. The control disc reached this point at almost three times higher force load than the 3D-printed discs, due to its stiffer material properties. The force required for the 3D-printed discs to reach N=5 was consistent regardless of print layer alignment. This is further discussed in Section 3.2 with the FEA data. There was slight variation in the stiffness of VeroClear, however it seems to minimally affect the overall stiffness of the particle shape.

Figure 7. Top row – 3D representations of the discs to show print layer orientation with respect to the steel plates (A) parallel - 0° (B) parallel - 45° (C) parallel - 90° (D) perpendicular and (E) isotropic. Middle row – Images of first recorded (N=1) isochromatic stress fringe observed under low load for each respective disc. Bottom row - Images of the fifth (N=5) isochromatic stress fringe observed under low load for each respective disc.

Visualization of the stress fringes over increasing force loads permitted calibration of the materials for calculation of the stress optic coefficients (SOC). Following the approach of Daniels *et al.* [5], Figure 8 plots the normalized force load with respect the disc diameter (kN/m) against the first six isochromatic stress fringes observed on the discs [6]. The normalized force required for the soft polyurethane materials to achieve the same number of fringes were significantly less; approximately 150 - 500 fold difference depending on the type of polyurethane material. It was found that approximately 150 kN/m force per meter was required to achieve five fringes for the 3D-printed discs. In contrast, close to 500 kN/m was required to achieve the same for the acrylic discs. The contrast between the sensitivity of the optical properties for the two materials are clearly shown. The SOC value was calculated for by using the gradient of the slope at the given wavelength [26] which in this study was 589 nm. Our data exhibits higher force requirements compared with Daniels *et al.*, which is consistent since these materials are much stiffer than the urethane materials used in their study.

Although from Figure 7, it is shown that while the pressure at which the first recorded stress fringe appears depends on the particular print direction and orientation on the compression plates, the calibration shows that the mechanical force required remains consistent. The steady compressive strength for the different layer orientations supports the work published by Wang *et al.* [27] who reported little standard deviation in the compressive strength of VeroClear based on different print configurations. VeroClear is an acrylate-based UV curable resin, which deforms like a ductile material [18]. Manufacturer formulations are subject to alteration from time to time, thus re-calibration of the SOC is advised for each new batch. On the other hand, acrylic sheets are made from bulk polymerization to form the rigid thermoplastic poly(methyl methacrylate), which does not deform in the same way as VeroClear.

Figure 8. Graph for the calibration of F_α for the discs in VeroClear and acrylic materials. The 3D printed disc: VeroClear with 'parallel' Δ (average taken for 0°, 45° and 90°) and 'perpendicular' ○ print layers with respect to the compression plates. The laser cute disc: Acrylic □.

3.2 Finite element analysis of the disc stress visualization

The experimental material properties were required for input into the FEA model. Therefore, the VeroClear mechanical properties were tested according to the ASTM tensile and compression standards for plastics. Table 1 summarizes the material values generated for VeroClear in this study. It was found that under low loads, there was no significant difference in the elastic modulus with respect to print layer orientation. Since the optical behavior of the perpendicular printed disc was most in line with the control disc (an isotropic material) the FEA model was treated in the same way. We found the material stiffness varied minimally with respect to the print layer orientation under low loads.

For the simple disc shape, the isochromatic stress fringes were modeled in FEA to show the principal stress regions. It is important to note that FEA produces iso-surface mesh, which means that the highlighted regions of stress apply only to the surface being viewed. It is assumed that the shape remains constant through the cross-section of the disc, and the principal stress also remains constant all the way through. Table 2 compares the experimental and computational data for the 2D disc at N=5. The load requirement and displacement needed to obtain N=5 in the FEA simulation was in good agreement with the experiment. The slight discrepancy between the force load from the experiment and the FEA could be accounted for the simple linear model used for the material in the FEA, since the compressions were kept to low loads and small displacement. A model which takes into account complete material properties and deformation of the disc is likely to produce results closer to that of the experimental. For this reason, the FEA was used purely for the visual validation of the principal stress of the irregular shape.

Table 1. Material mechanical properties of VeroClear and Acrylic generated according to the ATSM D638 and D695 standards and values reported in literature.

Table 2. Experimental data for force load measurements taken directly from the Instron for 5 isochromatic fringes (N=5). The compressed discs 3D printed in VeroClear (parallel & perpendicular layers) and for the control disc. Comparative FEA data for VeroClear.

Of interest was the asymmetrical fringe pattern exhibited by the 45degree rotated specimen, as this behaviour could not be replicated using the linear isotropic material model. It was found that implementing a 2D orthotropic model and significantly decreasing the elastic modulus in one axis produced a similar asymmetric pattern. Figure 9 illustrates the first recorded isochromatic stress fringe (N=1) for the disc both in the experiment and FEA using this method. However, this anisotropic material model conflicts with experimental test data, and lacks an accurate shear modulus value. A more detailed investigation into the anisotropic material properties and their effect on photoelastic properties was beyond the scope of this study but is something that should be explored in future. The use of adjustable waveplates to eliminate the additional rotation of light by the acrylic would overcome this difficulty.

Figure 9. Image of particle under load to give N=1 for (A) 3D-printed disc with parallel layers at the 45° orientation and (B) the disc in the FEA with the transverse isotropic material model.

3.3 Stress visualization of complex 3D-printed shape

The coffee beans were compressed in the upright position (bean line perpendicular to the steel plates). Compressing the bean on its side (bean line parallel to the steel plates) was possible but the experiments were not repeatable due to the irregularity of the shape and instability in that position. Figure 10 shows the image of (Fig 10A) the real bean, (Fig 10B) the Computer Aided Model of the bean and (Fig 10C) the final 3D-printed bean in VeroClear.

Figure 10. Image of (A) real coffee bean (B) CAD model of coffee bean and (C) 3D-printed coffee bean. Dimensions of (A) 11 mm length, 4mm thickness and 7 mm height and (B, C) 22 mm length, 14 mm width and 8 mm thickness.

The coffee bean designs were 3D-printed in the perpendicular orientation (as shown in Fig. 6D) so the traditionally observed photoelastic response is observed and the print layers have minimal influence. Figure 11 shows in the top row images of the decaffeinated bean and the bottom row contains images of the bean with solid internals. Figure 11A shows the uncompressed beans, and from the front view the voids are clearly visible inside the decaffeinated bean. In addition, a shadow is observed in the outer edge of both 3D-particles. As the particles were additively manufactured, the shadow is believed to be caused by refraction at the multiple faces of the complex shape and not by frozen internal stress. The shadow effect could be eliminated by surrounding the particle with media of matching refractive index (RI). This hypothesis was validated by ray tracing of the uncompressed particle, as shown in Figure 11C and 11D, where a ray was passed through the particle with matching and non-matching RI, respectively. It was shown that the media with matching RI media eliminates the shadow, whereas when the RI varies to the bean aa matching shadow to the experiment is observed. Figure 11B shows the compressed 3D-printed coffee beans. Clear stress visualization was not observed for the bean with voids due to the 3-Dimensional complexity in the x, y, and z axis directions throughout the cross-section of the particle. In contrast, the stress fringes were clearly visible in the solid bean.

As observed with the 2D disc shape, the isochromatic fringes originated from the diametric contact points. Conversely, the contact points on the compressed solid bean appear to be binary. The fringes appear to be originating in the same diametric contact points, but pulsing in two different directions, one on either side of the bean line. This photoelastic response of the solid 3D particle is observed through the front only and it is possible that the curved particle shape causes a lensing effect.

Figure 11. Top row – Images of decaffeinated coffee bean with voids, Bottom row –Images of solid coffee bean. Experimental images of (A) Uncompressed coffee bean (B) photoelastic response of coffee bean. Ray tracing images of uncompressed coffee bean surrounded by (C) media with matching refractive index and (D) media with non-matching refractive index (same as experiment)

An approach called the 'frozen-stress technique ' has been reported in literature, where an X-ray CT scan of a soil sample with inherent internal fractures was compressed under conditions which captured and locked in the internal stress [28]. Using this technique, slices through the cross-section were able to be taken of the experimental sample after compression and directly compared to the FEA. It is important to note that the sample must be a stable shape which can keep upright without modification to the design or support. Therefore, to try and observe the photoelastic response inside the bean with the internal voids, a different approach had to be taken. A thin slice from the cross-section of the particle was taken, digitally extruded to 10-mm thickness, and 3D-printed. This was done to aid in understanding the formation of principal stress fringes around the voids. Thus, the photoelastic response of the regions with high and low stress inside the bean were visualized. Figure 12A shows the experimental photoelastic compression of the bean slice at 0.25-mm displacement. The comparative 2-Dimensional FEA analysis of the digitally extruded cross-section demonstrated good agreement with respect to the formation of isochromatic fringes, particularly regions of high stress around the voids (Fig 12B). Additionally, compression of the particle eventually led to particle fracture.

Figure 12. Photoelastic response of the (A) 3D-printed digitally extruded cross-section of the coffee bean with internal voids and (B) FEA simulation, both to 0.25 mm displacement.

3.4 Stress quantification of 3D-printed particles using gradient-squared method

Quantification of the stress for complex shapes is extremely difficult to achieve for many reasons. Current methods are only calibrated to quantify stress for 1D or 2D shapes, specifically perfectly round or ellipsoid shapes. A 3D model with external irregularities would require an algorithm specific to that shape. Any alteration to the shape would mean the algorithm no longer applies, thus impacting the accuracy of the analysis. Furthermore, if a shape were to in addition have complex internal structure, then that can further complicate the algorithm. Currently there are no solutions to this problem. The gradient squared method (G^2) is the closest method which could be used for such particles. It is an approach which has been used to measure the empirical 2D stress of particles (mainly discs) by quantifying the amount of light intensity produced over increasing force loads. This method, to the best of our knowledge, has not been reported on 3D-printed discs. Although it has been reported using X-ray radiography for the study of stress birefringence of granular packing in 3 dimensions [29], it has never been applied to 3D-printed particles of complex or porous geometries.

Semi-quantitative stress measurements have been applied to conventionally flat, but non-circular, particle shapes by *Zhao et al. [30]*, and we perform a similar analysis here. Figure 13 illustrates the plot of the light intensity produced from the compression videos of the particles against the respective normalized force loads.

The gradient in light intensity exhibited by the control disc (Fig 13D) shows a linear trend line (R-squared value of 0.96). All particles, except the 3D coffee bean, monotonically increased comparable to the control disc. However, the gradient in the light intensity was much higher for VeroClear than the acrylic material; this could be due to the difference in stress optic coefficient. The error in the gradient in the light intensity increased for the 3D printed 2-dimensional particle shapes as the stress increased. This could be due to effects caused by the material plastically deforming. The particles were cleaned prior to compression, however, the surface was used "as is" from the printer and not polished.

The 2D digitally extruded cross-section of the coffee bean displays a similar trend line to the 3D-printed 2D disc shape. This is a promising result as it suggests that the semi-quantitative stress measurement by means of the gradient-squared method can be applied to 2D shapes with complicated structures that also contain internal pores. The 3D coffee bean with solid internals does not behave in the same way as the other particles. This suggests that the G^2 method is better suited for particles with a constant 2D cross-section and that the irregularity of the external and internal particle shape is not a limitation for this method. Furthermore, the photoelastic response of 3D printed particles with 3-dimensional shape can be observed in a bath containing index-matched solution. Otherwise, the lensing effect would be observed due to the curved particle structure.

Figure 13. The gradient-squared (G^2) approach used to quantify the amount of light produced for the tested particles. The gradient squared light intensity plotted against the normalized force loads shown for the particles starting from top to bottom of graph: 2D VeroClear disc – perpendicular print layers (A), 2D digitally extruded cross-section of coffee bean (B), 2D VeroClear disc – parallel print layers (C), 2D acrylic disc (D) and 3D solid coffee bean (E).

4 Conclusions

In conclusion, this study investigated the internal-stress visualization of 3D-printed discs and found non-traditional optical photoelastic properties when the print layer was in parallel position to the compression plates. However, the mechanical properties were not significantly affected by the change in orientation of the print layer at the low loads. In addition, the photoelastic stress visualization of complex 3D coffee bean shape was successfully observed.

Intricate internal geometries make the stress visualization of 3D shapes difficult to observe. Thus, a digitally extruded 2D cross-section from the center of the bean was 3D-printed and compressed. FEA validated the regions of high and low stress, particularly around the internal voids, with the fringes in good agreement to the experimentally observed fringes. We also report, for the first time, the G^2 method applied to 3D-printed particles of simple and complex geometries for semi-quantification of the internal stress. It was found that a linear trend was produced for 2D shapes, whereas the method may not be best suited for 3D shapes.

Further comprehensive investigation is required into the VeroClear material properties to set up an anisotropic material model to observe photoelastic response, and to account for the rotation of polarization due to the material itself, beyond the superimposed photoelastic response. The work presented in this study unlocks potential for further investigation of the photoelastic stress visualization for complex particle geometries. This brings researchers one step closer to being able to understand the behavior of and model the stress within complex geometries.

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