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Voong, K. Y.; Norton, A. B.; Mills, T. B.; Norton, I. T.

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K.Y. Voong*, A.B. Norton, T.B. Mills, I.T. Norton

School of Chemical Engineering, University of Birmingham, Edgbaston, B15 2TT, United Kingdom

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ABSTRACT

Deep-fried battered and breaded coatings provide foods with texture, flavour, reduced moisture loss and oil uptake. The physical characteristics of deep-fried batter and breadcrumb coatings was investigated for deep-fried prawns. Previous data on the effect of breadcrumb size on the microstructure of the coating is limited, therefore breadcrumbs were divided using the following sieve sizes and then applied to the coating in order to investigate the effect of breadcrumb size on the physical and mechanical properties: 4.0 mm, 2.8 mm, 2.0 mm, 1.4 mm, 1.0 mm, 710 μm, 500 μm, 355 μm. After frying, internal morphology was studied using X-ray microCT showing that the total porosity of coatings decreases with breadcrumb size whilst pore size distribution and structure thickness distribution increased with breadcrumb size. As crispness is a fundamental sensorial property of deep-fried battered products, crispness was evaluated by uniaxial compression to acquire mechanical and acoustical measurements simultaneously. Results showed decreasing breadcrumb size reduced the number of multiple failures, reduced jagged appearance of the force profile was observed, reduced maximum compression force and acoustic emission, which has been used as a representative of crispness. This study provides evidence of the importance of breadcrumb size in deep-fried battered and breaded formulations.

1. Introduction to batter coatings

The palatability of deep-fried foods is due in part to its unique flavour, taste and texture (Fiszman & Salvador, 2003). The high temperatures used for frying results in a desirable texture that is recognised as a dry and crisp crust contrasting a moist and tender core (Mellema, 2003). As well as enhancing the texture, a crusted coating prevents dehydration of the core, aids browning and reducing oil uptake into the core (Altunakar, Sahin, & Sumnu, 2004). Deep-fat frying is a simultaneous process of heat and mass transfer whereby water and other soluble materials are lost from the material being fried as oil penetrates the product (Mellema, 2003).

Batter is a flour and water mixture with additional salt, gums and seasonings, two main types are recognised; adhesion batters or tempura-type batters (Varela & Fiszman, 2011). Adhesion batters act as an interface layer between product and breadcrumb coating (Fiszman & Salvador, 2003), whereas tempuras are leavened chemically to create a puffed texture (Xue & Ngadi, 2007). Battered and breaded products have grown in popularity and are assessed on appearance, uniformity of coating, colour, crispness, adhesion and flavour (Loewe, 1993). As a textural attribute, crispness perception has been shown to be a combination of tactile and auditory components and depends on macroscopic and microscopic features within the food (Vickers, 1988).

1.1. Deep-fat frying process

Products are typically coated with a predusting layer to absorb excess moisture and provide additional adhesion for batter and breadcrumb layer (Mukprasirt, Herald, Boyle, & Rausch, 2000). Battered and breaded products are fully submerged into cooking oil and as surface temperature of the coating rises rapidly, surface moisture is evaporated off to allow surface drying and shrinkage (Mellema, 2003). The temperature of surrounding oil subsequently decreases but is compensated for by convection (Mellema, 2003). Other chemical changes that occur during crust formation include protein denaturation, non-enzymatic browning, caramelisation of sugars, glass transitions, oxidation and starch gelatinisation (Altunakar et al., 2004). Development of a positive pressure gradient within the fried product causes moisture to be released as vapour via cracks, open capillaries or explosive evaporation, thus creating voids and entry points for oil to penetrate (Mellema, 2003). As vapour creates voids for oil penetration, it is suggested that oil uptake is largely determined by moisture content (Mellema, 2003). In fact, it has been shown that food with high moisture loss result in higher oil uptake (Gamble, Rice, & Selman, 1987). Therefore, moisture and oil content have a large influence on crisp texture. Studies focusing on the relationship between crispness and high moisture products are limited and measurement procedures are different depending on product type (Antonova, Mallikarjunan, & Duncan, 2003).

Oil that penetrates the voids act as both as a heat transfer mechanism and a final ingredient, with reports of up to 1/3 of the total products weight being oil (Mellema, 2003). High levels of oil ensure structural integrity of batter is maintained by preventing shrinkage and collapse, providing satiety but also posing as a health risk. Numerous studies have suggested that oil absorption occurs predominantly during post-frying cooling (Aguilera, Stanley, & Baker, 2000; Moreira, Sun, & Chen, 1997; Moreno & Bouchon, 2013).

1.2. Crispness perception

'Wet' crisp such as apples, contain fluid within their cells balanced by intracellular forces from strength and elasticity of the cell wall, thus creating turgidity (Vickers & Bourne, 1976). Rupture of these cell walls produces a sound pressure wave that is responsible for the perception of crispness (Vickers & Bourne, 1976). 'Dry' crisp such as potato chips have brittle cell walls with air-filled cavities (Duizer, 2001). A continuous force exceeding a threshold will bend and break this brittle material, fragments will bend back to their original shape, thus setting of vibrations and sound pressure wave (Vickers & Bourne, 1976). Deep-fried battered and breaded products have properties of both wet and dry crisp, in that they are cellular structures that contain both air and liquid oil.

A combination of acoustic and force deformation measurements can be used as an indication for oral crispness (Chen, Karlsson, & Povey, 2005; Duizer, 2001; Taniwaki & Kohyama, 2012). Humans perceive sound of cellular structure breakage via air conduction to the ear and bone conduction through the tongue, cheeks and mandible to the ear (Duizer, 2001). As low frequencies are absorbed by muscle tissue during bone conduction, the recordings of crispness are louder than sound perceived during mastication (De Belie, Harker, & De Baerdemaeker, 2002). When force is applied to a material, the stored strained energy is converted to acoustic energy, individual molecules in the air are displacing others causing a vibration and thus a sound wave is propagated.

1.3. Breadcrumb coating

Breadcrumb coating derives from baked bread that is dried and comminuted to form smaller sizes (Pickford, 2003). Breadcrumbs often consists of a mixture of sizes to create a non-uniform layer.

As battered and breaded products will have differences in morphology and composition between the layers, this study aims to characterise the physical properties of a battered and breaded coating only. Information on the effect of breadcrumb size is limited, this study aims to characterise the physical properties of breadcrumb coatings of different crumb size. Properties investigated included total porosity, pore size distribution, compression force and acoustic emission as indicators of crispness.

2. Materials & method

Standard samples consist of white prawns (spec 50–60, Hyperama Plc, UK) butterflied and deveined, then coated with predust flour, batter and then breadcrumb coating. To investigate the effect of breadcrumb size, breadcrumbs were separated using the following sieve apertures: 4.0 mm, 2.8 mm, 2.0 mm, 1.4 mm, 1.0 mm, 710 μm, 500 μm, 355 μm (Endecotts Ltd. London, England). Each size as an outer coating was investigated post-fry. All samples were fried in at 195 °C for 42 s in soya bean oil (Fryer model NPDF3, Parry Catering Ltd UK).

2.1. Coating pick-up

The amount of coating adhering to the sample prior to frying was calculated by the weight of coated sample divided by weight of sample before coating multiplied by 100. Pick-up percentage was calculated for each coating step (predust, batter, breadcrumb). To avoid batter dripping from the sample effecting the measurement of pick up, samples were allowed to drip for 30 s before weighing.

2.2. Moisture and oil content

Moisture and oil content were calculated for the coating post-fried to assess changes in moisture and oil content with breadcrumb size. Moisture content was determined by difference in weight after vacuum oven-drying for 24 h at 70 °C. Oil content was determined by Soxhlet solvent extraction for 5–6 h, followed by rotary evaporation. Samples were carried out in three replicates.

2.3. Confocal microscopy

Batter and breadcrumb coating cross-sections were stained after frying with Nile red (Sigma Aldrich 72485, UK) (0.01%) to observe the depth of oil penetration. A confocal microscope (Leica TCS SP5, Germany) was used to acquire images after exciting at 543 nm with a He/Ne laser. Image acquisition was performed at a pinhole size of 100 μm with 10× magnification objective lens.

2.4. X-ray micro computed tomography (MicroCT)

Samples were scanned using a voltage of 59 kV, current of 100 μA and no filter (Skyscan 1172, Bruker, Belgium). Samples were covered in parafilm to prevent moisture lost. NRecon, CTAn and CTVox was used to reconstruct images and carry out 3D analysis. Experiments were carried out in three replicates.

2.5. Texture and sound emission analysis

Compression testing was carried out using a TA XT plus Texture Analyser (Stable Micro Systems Ltd. UK) with 5 kg load cell, 3 g trigger force, P/40 cylindrical aluminum probe at a constant speed of 0.5 mm/s. Deep-fried battered and breaded coating were peeled from the substrate, cut into 20 mm diameter shapes and subjected to 60% compression ratio with top surface of the coating facing upwards.

Acoustic envelope detector (AED) (TA-XT Plus, Stable Micro Systems Ltd., UK) was used for force-displacement acoustic measurements and recorded using Texture Exponent. A microphone (12 mm diameter) was positioned 7 cm horizontally from center of platform. Calibration was carried out using a sound calibrator at 94 dB and 114 dB at 1000 Hz. Any background noise was filtered using 3.125 kHz corner frequency. A gain of AED was set at 3 with data acquisition rate set to 500 points per second for force and sound measurements. Ten replications were performed for each sample. Parameters extracted included: Maximum force, area under force curve, force peaks (drops in force above 0.049N), maximum sound pressure level and number of sound peaks (drop in sound pressure level above 10 dB).

2.6. Statistical analysis

One-way ANOVA and post-hoc Tukey test was performed to evaluate any differences between samples.

3. Results and discussion

3.1. Microstructure of fried batter and breadcrumb coatings

The microstructure of batter coatings has been previously explored with microscopy techniques (Llorca, Hernando, Pérez-Munuera, Fiszman, & Lluch, 2001; Moreno & Bouchon, 2013). The use of microscopy to study internal morphology of deep-fat fried batter is demonstrated in Fig. 1, which shows a decrease in fluorescence deeper within the coating, highlighting differences in structure throughout the
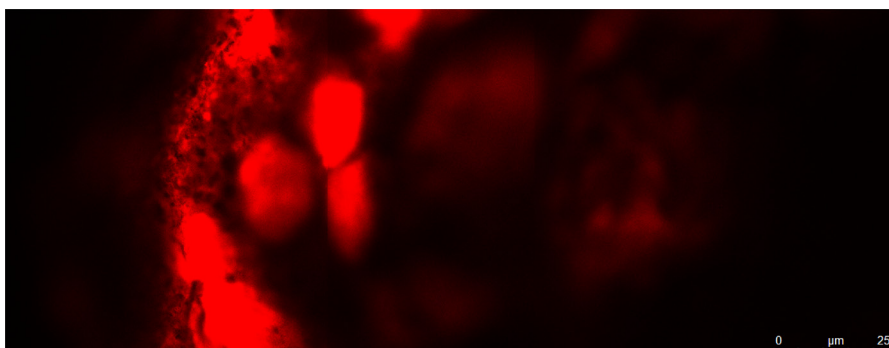
Fig. 1. CLSM image shows cross-section of fried batter and breadcrumb (not sieved) coating stained with Nile Red to observe depth of oil penetration. Stain shows differences in morphology at layers of the crust.

sample. Regions of high fluorescence are clustered at the surface of the coating, suggesting oil accumulates within breadcrumb pieces. This is in contrast to low fluorescence deeper within the coating, where moisture content is higher than at the surface and oil content is lower. The depth of oil penetration can also be observed; a longer fry time is required for deeper oil penetration.

Microscopy techniques are limited in terms of resolution and require laborious sample preparation. As a result, MicroCT has been employed in this study for its non-invasive and high resolution ability to quantify structural parameters; total porosity, pore size distribution and structural thickness. These physical parameters are structural modifications caused by heat and mass transfer during deep-fat frying, the degree of these structural changes will affect mass migration (Adedeji & Ngadi, 2011).

Surface topography influences batter oil drainage during cooling but an understanding of the internal morphology provides an indication of permeability and space for oil absorption (Moreno & Bouchon, 2013). Prior to scanning, the surface of coatings became visibly more uniform and with a smoother surface with decreasing breading size. 2D greyscale slices shown in Fig. 2 demonstrate that with decreasing breadcrumb size, coatings appear to be visibly thinner, large pores are clustered towards the top of the coating whilst the majority of small pores are seen towards the core. Pores shaded grey appear to have an attenuation for x-ray, suggesting they are filled with oil as opposed to air. A prominent batter layer can also be seen with decreasing breadcrumb size suggesting higher moisture content, which is supported by Table 1. Moisture content increases whilst oil content decreases with breadcrumb size, a high moisture layer suggests a soft and pliant core (Luyten, Plijter, Van Vliet, 2004).

As fried batter is a cellular structure, porosity is a structural property of interest and can be defined as the volume of pores relative to the volume of the entire matrix (Dogan, Sahin, & Sumnu, 2005). Total porosity is highest for coatings with the largest breadcrumb size (Fig. 3), a higher porosity has been shown to result in a higher perception of crispness (Van Koerten, Schutyser, Somsen, & Boom, 2015).

From Fig. 3, total porosity of breadcrumb coatings from apertures 4.0 mm and 2.8 mm are significantly different to those from 2.8 mm to 710 μm and 500 μm to control (batter without any breadcrumb), suggesting that total porosity decreases with breadcrumb size. This is evident from the 2D greyscale images (Fig. 2) that show the structure becoming thinner with decreasing breadcrumb size whilst a high moisture batter layer is more prominent. This can be explained as breadcrumb size decreases, breadcrumbs are able to provide an even distribution of coverage across the surface, as some batter loses adhesion during the frying process, a full coverage of breadcrumbs provides a sealed barrier to prevent batter being lost (Van Koerten et al., 2015). Subsequently, a longer fry time may be required for oil to penetrate the coating to create a porous structure. Evaporation of moisture at the surface is also quicker than moisture migration deeper within the

product, therefore a crisp crust is able to form (Van Koerten et al., 2015).

Studying the range of pore size within batter coatings were of interest because the presence of micropores is suggested to influence mass transfer during frying (Mellema, 2003). In fact, the smaller the pores the higher the amount of fat absorbed via capillary forces during cooling (Moreira et al., 1997).

MicroCT analysis of pore size distribution shows that coatings with the largest breadcrumb size (4.0 mm aperture) has the widest distribution of pore sizes and the largest pore sizes (Fig. 4). Whilst decreasing breadcrumb size shows a narrowing range in pore size distribution. In fact, breadcrumbs from less than 2.8 mm aperture shows the majority of pore sizes to be < 201 μm. This suggests that pore size is batter dependent for coatings with breadcrumbs < 2.8 mm aperture. This is in agreement with previous studies that showed pore size distribution for deep-fried breaded coatings to range between 9 and 201 μm (Adedeji & Ngadi, 2009). However, the effect of breadcrumb size on pore size was not investigated. A wide range of pore sizes creates heterogeneities within a structure with varying structural strength and fracture mechanics, this translates to a desirable crisp texture.

Fig. 4 shows that coatings with breadcrumb sizes greater than 2.8 mm suggest that pore size is breadcrumb dependent, therefore a wider distribution is seen. Total porosity and pore size co-determine the amount of oil that is absorbed into the structure and has been found to increase with frying time (Van Koerten et al., 2015). Therefore, the findings in this study demonstrate the importance of breadcrumb size in fried foods formulation.

As oil absorption is influenced by porosity and pore size, visualising the internal structure allows a clear understanding of the arrangement of pores and the degree of open and closed porosity (Fig. 5). Colour-coding analysis shows large breadcrumb coatings (Fig. 5A) to have a wider range and large pore sizes (> 1000 μm), smaller breadcrumb coatings (Fig. 5B) have a smaller range and smaller pore sizes (~ 500 μm). Fig. 5A shows pores to be more clustered in comparison to Fig. 5B, suggesting differences in structural thickness between breadcrumb coatings.

The matrix between the pores acts as a scaffolding for the structure, this structural thickness could provide an indication of mechanical strength and therefore affect compression force. Compression force would translate to the amount biting force required to fracture the structure, therefore an indication of crispness perception. MicroCT analysis has shown that the percentage volume for structural thickness for batter coatings varies with breadcrumb sizes (Fig. 6). Structural thickness range for large breadcrumb coatings (4.0 mm) is narrow (9–220 μm) but as breadcrumb size decreases, a wider range in structure thickness is seen (9–797 μm). As expected, structural thickness appears to be inversely proportional to pore size distribution and total porosity. All coatings also show porosity to be dominated by open pores as opposed to closed pores, meaning that the majority of pores are
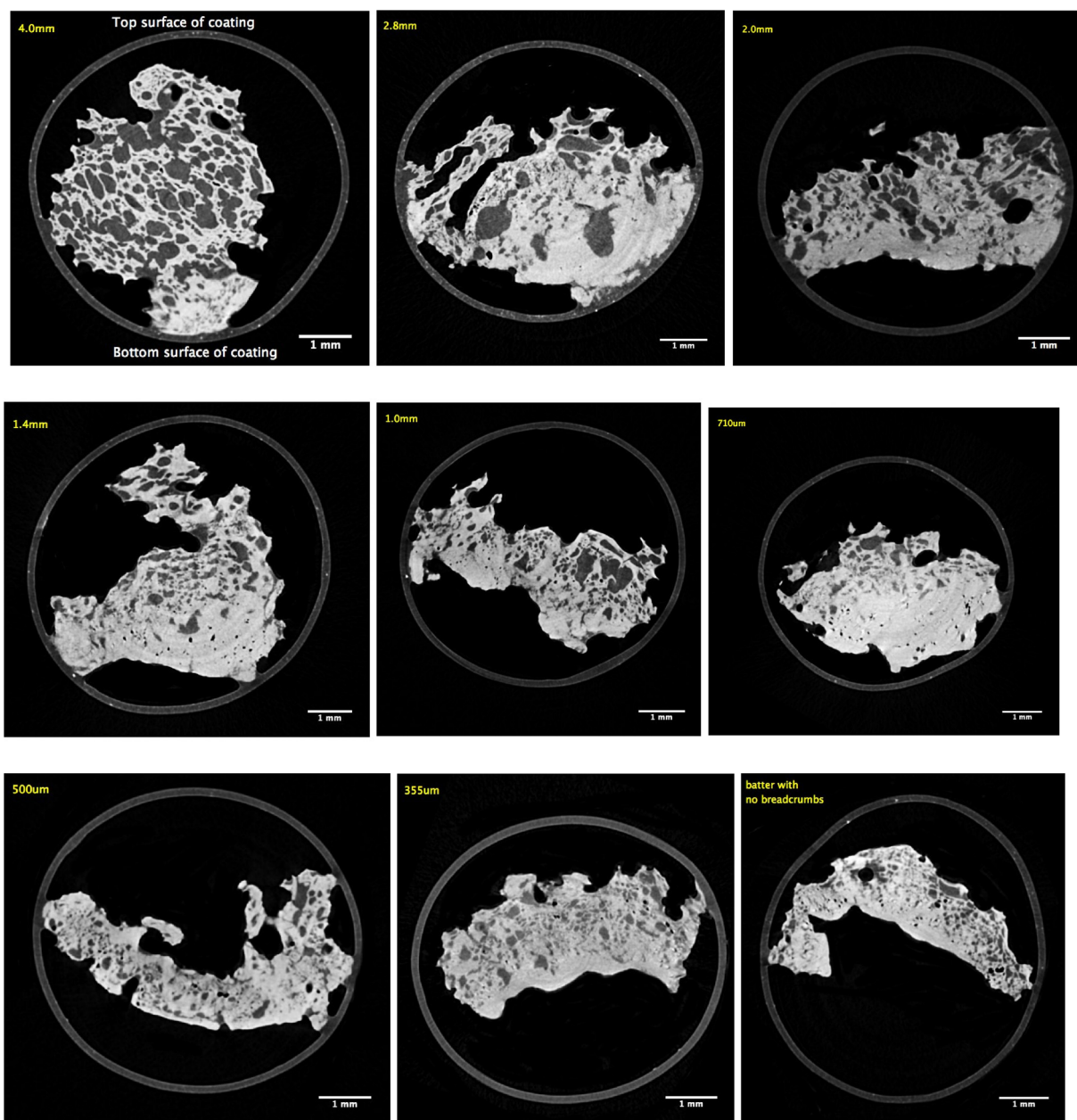
Fig. 2. MicroCT 2D-slice image of batter and breadcrumb coatings peeled away from the substrate post-frying. 2D-slice grey scale image displays differences in morphology from top surface (top of each image) to bottom surface (bottom of each image) of coating. Each image is labelled with size of aperture used to separate breadcrumb size.

interconnected. A higher proportion of open porosity allows space for oil to be deposited.

The strength of the matrix will also depend on material properties, moisture is lost during frying which enables a crisp crust to form. Moisture is a common plasticiser which enables mobility of polymers,

the composition of moisture within the matrix will change during frying (Luyten et al., 2004). Therefore the concentration will affect the mechanics of the protein and starch matrix and subsequently affect fracture propagation (Luyten et al., 2004). The loss of crispness by moisture plasticiser is also governed by the glass transition phenomenon (Slade &

Table 1
Moisture content percentage (wt/wt) and oil content percentage (wt/wt) of deep-fried battered and breadcrumb coatings with variable breadcrumb sizes. Results for largest (4.0 mm), intermediate (2.0 mm, 1.4 mm, 1.0 mm) and smallest (500 μm, 355 μm) breadcrumb size have been stated for oil content percentage. Decreasing breadcrumb coating size show a general increase in moisture content and decrease in oil content.

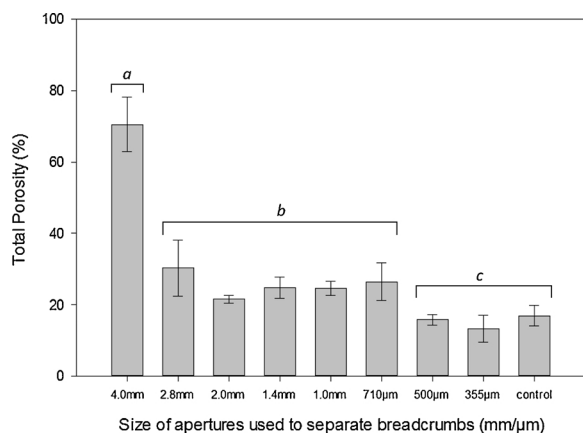|	Standard coating	4.0 mm	2.8 mm	2.0 mm	1.4 mm	1.0 mm	710 μm	500 μm	355 μm	Batter only
Moisture content % (wt/wt)	23.8 (± 1.8)	26.3 (± 1.4)	26.3 (± 3.3)	27.0 (± 2.8)	29.8 (± 0.1)	31.8 (± 1.6)	32.0 (± 1.9)	33.9 (± 3.0)	35.3 (± 1.1)	50.6 (± 2.6)
Oil content% (wt/wt)	49.1 (± 4.3)	42.8 (± 1.3)	–	41.6 (± 0.9)	41.6 (± 1.0)	41.1 (± 1.8)	–	40.0 (± 1.2)	33.8 (± 0.6)	–

Fig. 3. Summary of total porosity of batter and breadcrumb coatings from MicroCT analysis. 8 sizes of breadcrumb coating used with apertures listed. Identical letters indicate no significant difference at p > 0.05 according to Tukeys HSD.

Levine, 1995). Therefore, an understanding of components such as starch matrix and protein-rich phases is necessary to understand the crisp texture. Thermal and rheological properties will also assist in understanding the phase transitions during the frying and aging process.

3.2. Texture and acoustic emission analysis of crispness

The effect of breadcrumb size on acoustic emission has been previously investigated and no significant differences were found (Maskat & Kerr, 2002). However, the size of breadcrumbs investigated were separated using a mesh size ranging 250–850 μm (Maskat & Kerr, 2002), this study focuses on a wider range of apertures and therefore a wider range of breadcrumb sizes.

In terms of texture analysis, battered and breaded coatings have been previously analysed by separating from the core before and after frying (Fan, Singh, & Pinthus, 1997; Maskat & Kerr, 2002). This study focuses on the deformation of the coating alone, however, during

mastication the deformation of the coating will also depend on the mechanics of the high moisture core, where a combination of compression and shear are involved (Luyten et al., 2004).

As expected with crisp foods, the force-deformation profiles show multiple fracture events (Fig. 7), which is indicative of fracture events occurring simultaneously and is perceived as crispness (Maskat & Kerr, 2002). Once fracture stress, fracture energy and critical stress intensity have been reached, fracture will begin again at the top of the curve (Luyten & Vliet, 1995). The force that is required for subsequent fractures will depend on the composition of material and size of previous fractures (Luyten et al., 2004). This jagged behavior is particularly prominent of large breadcrumb coatings (4.0 mm and 2.8 mm aperture), this can be explained as battered and breaded coatings consist of a high moisture core and a rough uneven surface. A highly rough surface is due to breadcrumbs lack of ability to merge with the batter. Smaller breadcrumbs are able to merge and be contained within the batter to form a smooth and uniform layer which is able to retain more moisture than large breading size coatings (Maskat & Kerr, 2002). A higher retained moisture content explains why a lower compression force is required to compress 60% strain of smaller breadcrumb coatings and reduced jagged behaviour is seen (Fig. 7).

Breadcrumb structure contains regions of defects that are weaker in strength, this could be due to differences in meso-structure e.g. ingredients have phase separated (Scanlon & Zghal, 2001). This results in stress being concentrated and a fracture point is created (Luyten & Vliet, 1995; Vincent, Jeronimidis, Khan, & Luyten, 1991). Once crack propagation has begun, the surrounding material around the crack relaxes and any stored elastic energy becomes available for acoustic emission or reshaping the deformed structure (Luyten et al., 2004).

The relationship between force drops and sound pressure level (SPL) can be in one-to-one correspondence (Chen et al., 2005), indicating large structural breakdown to be accompanied by high SPL. However, as shown in Fig. 8 this is not always true, multiple acoustic peaks are due to heterogeneities in the microstructure (porosity, pore size, structural thickness, high moisture core), therefore multiple crack and fracture events are occurring simultaneously. Sound peaks occur as the sample begins to deform and last for the entire duration of testing.

Fig. 8 and Table 2 shows that both large (4.0 mm aperture) and
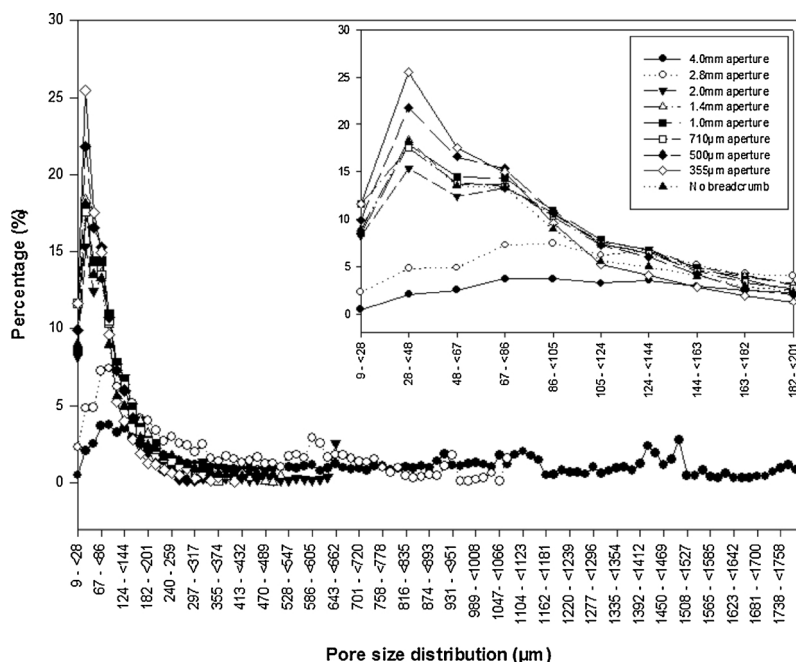

Fig. 4. MicoCT analysis of pore size distribution of batter and breadcrumb coatings. Distribution between 9 and 201 μm has been highlighted as shown in graph in right hand corner.
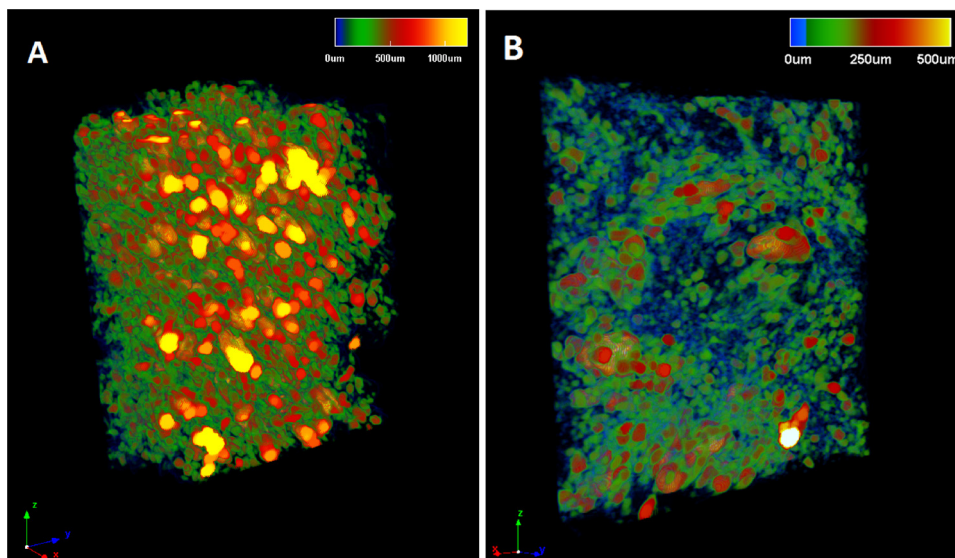
Fig. 5. MicroCT analysis of pore size distribution processed by CTVox into colour coded 3D model of A) Breadcrumb coating form 4.0 mm aperture B) Breadcrumb coating from 1.4 mm aperture.
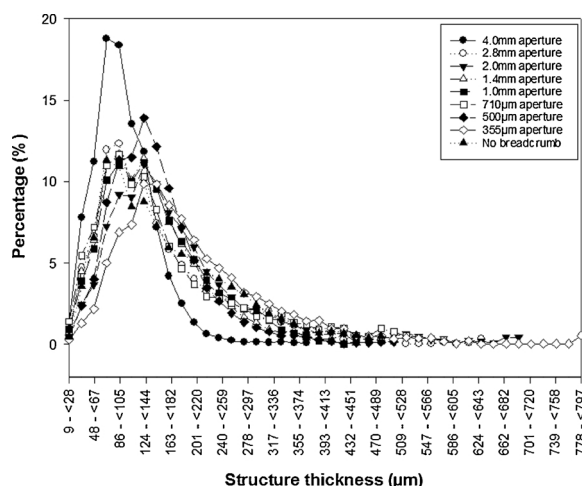

Fig. 6. MicroCT analysis of structure thickness distribution for batter and breadcrumb coatings.
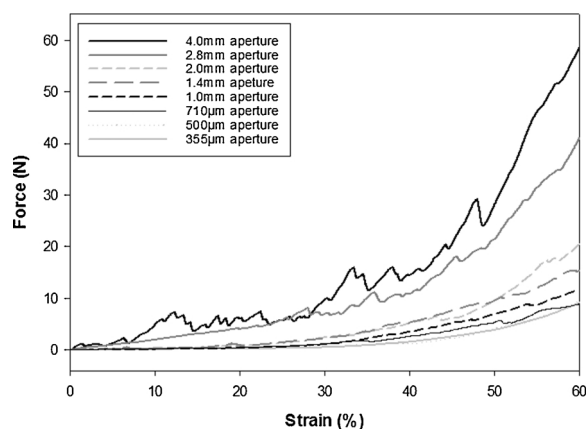

Fig. 7. Texture analysis force profile of batter and breadcrumb coatings with variable breadcrumb sizes.

small (1.4 mm aperture) breadcrumb coatings to have the similar peak SPL (> 70 dB), however the number of sound peaks decreases significantly with smaller breadcrumbs (86.2–14.4) due to a smoother coverage over the battered substrate. SPL values and sound intensity has been previously found to be lower for less crisp products and high moisture (Seymour & Ann, 1988).

Table 2 presents the acoustic and mechanical parameters for deep-fried battered and breaded coatings with variable breadcrumb size. Maximum force, force peaks (drops in force more than 0.049N), area, SPL and number of sound peaks show significant decrease with breadcrumb size.

Maximum force is representative of hardness, whilst area under the force curve is representative of the work of compression or toughness. Both parameters decrease with breadcrumb size, this can be explained as although structural thickness increases with smaller breadcrumb size (Fig. 6) moisture content also increases (Table 1) resulting in reduced structural stiffness and crispness perception.

Force peaks are indicative of jaggedness of the force profile curve (Salvador, Varela, Sanz, & Fiszman, 2009), as supported by Fig. 7, a jagged curve with several fracture events is typical of a crispy products (Salvador et al., 2009).

Table 2 shows that large breadcrumb coatings (4.0 mm) show high SPL and number of sound peaks, which is indicative of a loud, brittle and weak structure with many structural breakdowns (Salvador et al., 2009) and so can be perceived as more crisp than samples with low SPL and low number of sound peaks. The fracture and acoustic behaviour of cellular structures such as fried batter has been shown to depend on composition of microstructure.

4. Conclusion

This research has demonstrated the importance of breadcrumb size on the physical and mechanical properties of fried batter coatings. MicroCT has enabled structural parameters such as total porosity, pore size distribution and structural thickness to be quantified and provide an in depth understanding of the internal microstructure of batter and breadcrumb coatings. Morphological parameters such as porosity is necessary to relate mechanics of the solid matrix to product behaviour but also for understanding the degree of mass transfer between oil and water.

As breadcrumb coatings decrease from 4.0 mm aperture to 355 μm aperture, total porosity, maximum compression force, area, sound pressure level, force peaks and number of sound peaks decreases. Simultaneously, pore size distribution and moisture content increases,
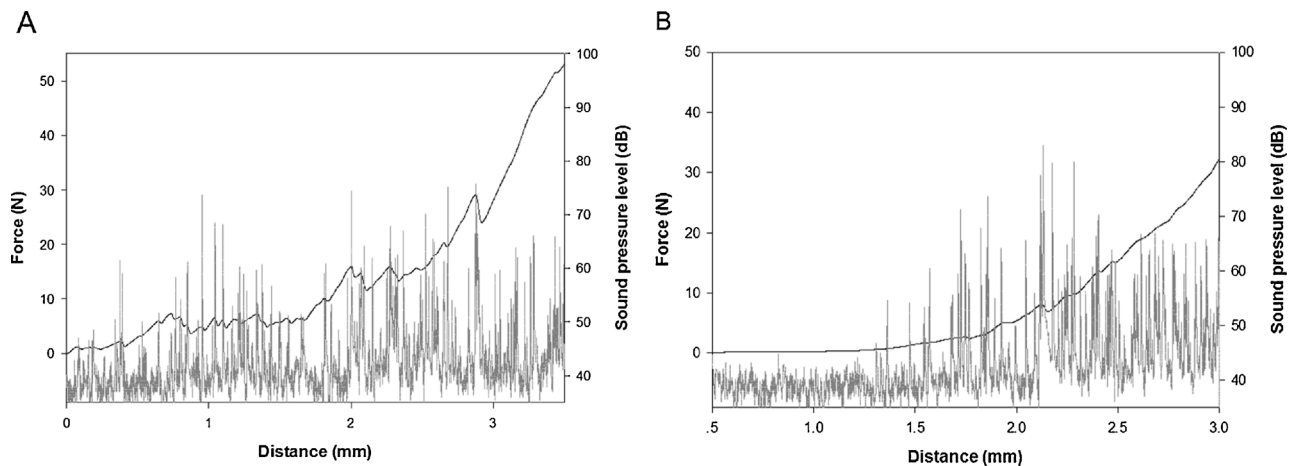
Fig. 8. Force-displacement of sound pressure level (dB), force (N) versus Distance (mm) for A) breadcrumb coating from 4.0 mm aperture B) breadcrumb coating from 1.4 mm aperture.

Table 2
Mean values of mechanical and acoustic parameters from texture analyser and AED for batter and breadcrumb coatings with varying breadcrumb size. [abcde] Different letters for the same row refer to a significant difference (p < 0.05) according to Tukey's Test.

Parameter	4.0 mm	2.8 mm	2.0 mm	1.4 mm	1.0 mm	710 μm	500 μm	355 μm
Max Force (N)	45.5 ± 8.6[a]	29.82 ± 5.6[b]	21.4 ± 2.8[c]	12.5 ± 2.7[d]	13.3 ± 4.9[d]	9.33 ± 3.6[de]	7.48 ± 2.7[de]	4.95 ± 2.0[e]
Area (N.sec)	84.5 ± 24.5[a]	49.0 ± 8.5[b]	34.6 ± 5.9[b]	16.2 ± 5.4[c]	18.9 ± 10.6[c]	8.94 ± 4.5[c]	7.64 ± 2.1[c]	4.5 ± 1.0[c]
Force peaks (drops in force more than 0.049N)	0.88 ± 0.3[a]	0.881 ± 0.8[a]	0.36 ± 0.1[b]	0.28 ± 0.2[b]	0.35 ± 0.3[b]	0.16 ± 0.1[b]	0.17 ± 0.1[b]	0.13 ± 0.1[b]
Max SPL (dB)	75.1 ± 4.6[a]	74.3 ± 3.6[ab]	72.9 ± 5.9[ab]	73.3 ± 4.4[ab]	75.7 ± 2.3[a]	74.7 ± 7.4[a]	70.89 ± 5.3[ab]	67.8 ± 3.1[b]
Number of sound peaks	86.2 ± 29.2[a]	62.4 ± 17.9[b]	55.9 ± 12.2[b]	39.6 ± 15.8[b]	39.9 ± 11.3[b]	33.0 ± 13.2[b]	32.6 ± 14.0[b]	14.4 ± 4.9[c]

these parameters collectively could result in reduced crispness perception. Reduced crispness perception will also be due to changes in the solid matrix, therefore material properties and composition could be investigated. Results shown in this study provide an indication of instrumental testing for crispness. As crispness is a sensorial attribute, further work will look to correlate instrumental measurements with sensory testing.

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